An Empirical Measurement Study of Free Live Streaming Services

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Abstract. Live streaming is one of the most popular Internet activities. Nowadays, there has been an increase in free live streaming (FLS) services that provide unauthorized broadcasting of live events, attracting millions of viewers. These opportunistic providers often have modest network infrastructures, and monetize their services through advertising and data analytics, which raises concerns about the performance, quality of experience, and user privacy when using these services. In this paper, we measure and analyze the behaviour of 20 FLS sports sites on Android smartphones, focusing on packet-level, video player, and privacy aspects. In addition, we compare FLS services with two legitimate online sports networks. Our measurement results show that FLS sites suffer from scalability issues during highly-popular events, deliver lower QoE than legitimate providers, and often use obscure and/or suspicious tracking services. Caution is thus advised when using FLS services.

Keywords: Network Traffic Measurement · Free Live Streaming · Quality of Service (QoS) · Quality of Experience (QoE) · Privacy.

1 Introduction

In 1995, a company called Progressive Networks[1] broadcast the first live sports streaming event on the Internet, featuring a baseball game between the Seattle Mariners and the New York Yankees [26]. Since then, the growing adoption of smartphones and the emerging mobile Internet (i.e., 4G, 5G, and LTE technologies) have enabled users to watch live events from anywhere without much difficulty. Mobile video streaming, including live streaming, currently accounts for 75% of total mobile data traffic [6]. This high demand for video streaming is both an opportunity and a challenge for network service providers.

For users, the Quality of Experience (QoE) for video streaming is important [10]. Measuring QoE can be done either with a subjective approach in which human viewers rate video sessions on a Mean Opinion Score (MOS) scale, or an objective approach that collects information from different protocol layers and uses mathematical models to estimate QoE for the video content [27]. Since

[1] https://www.realnetworks.com

measuring QoE is challenging, there are several studies that map network-level Quality of Service (QoS) parameters to user QoE [23]. This paper focuses on network-level and video QoS parameters that impact QoE.

The growth in popularity for live sports streaming has led to the emergence of many free live streaming (FLS) sites. However, using these unauthorized and unregulated providers raises concerns about QoS, QoE, and user privacy. For instance, these FLS sites may not have adequate network infrastructure to deliver scalable services, and as a consequence, both QoS and QoE may suffer. Furthermore, many of these FLS sites recoup their operational costs through advertising and data analytics, which raises concerns about what user-level information is collected by these sites, and where such information is sent.

Prior research efforts have focused on blocking live broadcasting sites [21,29], or detecting security leaks in FLS sites [25]. However, many Internet users still seek out these free sites despite their awareness of security concerns, and the number of FLS sites and users continues to proliferate [1].

In this paper, our basic premise is that users should be aware of the many tradeoffs associated with video streaming sites, including performance (i.e., QoS and QoE) as well as security and privacy. We study live sports streaming from both free and legitimate sites, doing so from these different viewpoints. The purpose of our study is to provide better insight into how video providers deliver their services, and what QoS is provided. Based on these insights, users can make better-informed decisions about using these services or not.

The research questions in our work are the following:

- What are the performance characteristics of FLS providers?
- What is the network and video QoS provided by FLS services?
- Are these services scalable for popular events?
- What privacy risks are associated with these services?

To study live sports streaming, we collected network traffic measurement datasets from several FLS sports sites during NHL, NBA, NFL, and UEFA (soccer) games in the 2019-2020 season. To capture video streaming sessions, we customized an existing mobile video streaming measurement tool [18] to study these services from different viewpoints. Also, we compared the FLS results with streaming from two popular monthly-paid service providers (TSN and DAZN). This comparison is motivated in part by the well-known adage: "If you are not paying for the service, then YOU are the product being sold".

The main contributions of this paper are as follows:

- We conduct a network traffic measurement study of FLS sports sites during selected NHL, NBA, NFL, and UEFA games in the 2019-2020 season.
- We measure and analyze the delivered network and video QoS for FLS services on a smartphone.
- We compare the live video streaming from FLS Web sites with two well-known monthly paid online sports networks.
- We investigate privacy concerns when using FLS services on smartphones.

The rest of this paper is organized as follows. Section 2 provides background on FLS. Section 3 describes our experimental methodology, measurement environment, and data collection process. Section 4 presents our measurement results. Section 5 summarizes prior related work. Section 6 concludes the paper.

2 Free Live Streaming

FLS services provide an infrastructure that allows Internet users to watch live events for free. Users can access live streams (usually without the owner's permission) even without registration [13]. In these services, the channels are neither catalogued nor listed in directories, and are not searchable via the Web site. Instead, the channel owner usually shares the channel links in online social network communities in order to reach viewers. One example is Reddit, a popular online social network on which users discuss, share, and rate Web content.

There are five major players in the FLS ecosystem: *Media Providers* that provide and stream the media content; *Channel Providers* that receive live streams from media providers and serve them to users; *Aggregators* that provide a list of available streams for users to browse; *Advertisers* that support the foregoing three entities through ads and overlays; and *Users* that watch their favourite live stream events found via the aggregators [1].

Sports streaming services are popular and constantly evolving [25,30]. In this paper, we study Web-based sports FLS services from a vantage point in Canada.

3 Measurement Methodology

Analyzing live video streaming on smartphone devices faces many challenges [8]. Video streaming characteristics such as QoE have to be observed to see how the user might react. Also, a multimedia stream may be encoded using different video codecs, devices may receive different resolutions and bitrates, depending on their screen size, location, end-to-end network status, membership type, etc. Processing and analyzing the captured traffic is another challenge, because of the voluminous network traffic involved. Furthermore, encryption makes measurement and analysis more difficult.

We used MoVIE [18], an open-source mobile video streaming analyzer, to capture and analyze live video sessions on an Android smartphone. MoVIE provides a multi-level view of video streaming by intercepting and analyzing all incoming/outgoing network traffic of a smartphone. MoVIE analyzes video streaming at the packet-level, flow-level, and video player level. We extended the existing MoVIE tool by adding a Privacy View component to its Traffic Interceptor component. We leveraged EasyList[2] from the ad-blocker community to investigate the generated flows to find potential ads, trackers, and malicious connections.

Figure 1 illustrates the architecture of MoVIE, which consists of seven components: Traffic Interceptor, Packet Tracer, Player View, Privacy View, Mapper, Main, and Graphical User Interface. For more details about MoVIE, see [18].

[2] `https://www.easylist.to`

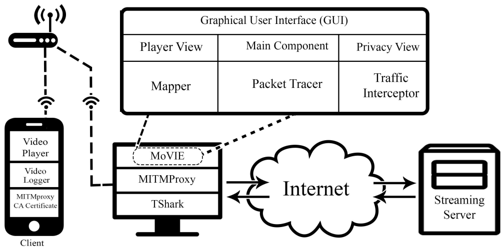


Fig. 1. System structure of MoVIE tool for Mobile Video Information Extraction

3.1 Experimental Setup

We set up a controlled measurement environment similar to Figure 1 to capture the transmitted packets, flows, and video player activities during live streaming events. Table 1 shows our system specifications. The mobile device and the PC

Table 1. Experimental Setup for Measurements

Device	OS	CPU	Cores	RAM	Video Player
Smartphone	Android 8.1.0	2.15 GHz	4	4 GB	Google Chrome v 71
PC	Ubuntu 18.4	3.6 GHz	8	8 GB	Google Chrome v 79.0.3945

were set up to use the same WiFi access point. We ran MoVIE on a Linux PC running MITMproxy [7] to intercept the network traffic, and Wireshark to capture traces of the Internet traffic generated by the smartphone. MoVIE captured all video player activities using an Android application that exploits the Google Chrome media feature.

All video streaming sessions were streamed using the Google Chrome browser. We performed a factory reset to ensure that other software or previous experiments do not impact our experiments. In addition, we updated the OS and pre-installed apps to the latest versions. We cleared the browser history and cache before each streaming session. During each session, the Chrome browser played video streams on the smartphone, while Wireshark and MoVIE were running on the PC to capture network traffic at the packet level. For each FLS Web site, we captured a video streaming session of 1-5 minutes in duration.

Since MITMproxy v4.0 is not able to decrypt HTTPS traffic from an updated Android device, we designed our setup to decrypt Android traffic on a single smartphone under test. To do this, we rooted the Android mobile device by using the Magisk tool. Rooting allows a user to have root access to the Android operating system with privileged access to modify code or install software that the vendor would not normally allow. Then we installed Xposed version 90-beta3 to install the Charles proxy certificate in system mode. Finally, we installed a CA

Certificate on the mobile device. Charles proxy[3] version 4.2.8 was installed on the PC to capture and decrypt all SSL connections generated from the smartphone. We used this setup to provide more data for privacy analysis.

Once the measurement environment was set up, we started the data collection tools on the PC and the video streaming on the mobile device. After capturing all network traffic, we used MoVIE to analyze the data.

3.2 Data Collection

To collect our dataset, we focused on FLS Web sites that are shared in sports-themed sections on Reddit. We monitored these forums during the NHL, NBA, NFL, and UEFA Champions League 2019-2020 season to find popular FLS providers.

Reddit has subreddits, which are like a Web forum in which users discuss and share content. Reddit differs from other social networks like Twitter, Instagram, or Facebook in that subreddits are openly accessible. The shared content is not limited to registered users, members, or friends. Users can access shared content and links without logging in. Ayers et al. [1] analyzed the data gathered from Alexa and SimilarWeb[4] and observed that the Reddit community receives up to 86 million visits a month from users looking for sports streams.

We observed that free sports streams are usually aggregated and shared in a few popular subreddits. In these subreddits, users can like or dislike shared FLS Web sites. Web sites with more likes increase in popularity and rise to the top of the Web page, and have a higher chance to attract even more visitors. Although there are approaches to automatically crawl and discover aggregator Web sites using online search engines [1], we found that most FLS pages are not reachable via search engines. Furthermore, service providers delete pages after the events. For these reasons, we manually selected the top-5 most popular FLS Web sites based on user votes for each of NHL, NBA, NFL, and UEFA events.

To compare the performance of FLS services with legitimate providers, we considered several features from the packet-level to the application-level. Since streaming sports events are geo-restricted and specific sports events are available only through specific online sports channels within each region, we subscribed to two Canadian online sports channels. The main sports provider in Canada is *TSN* (The Sports Network), which holds the Canadian rights to the top sports events. We also study *DAZN*, a relatively new sports streaming service in Canada.

Our collected dataset is composed of the top-5 popular (according to the likes from users) FLS Web sites in four popular sports, as gathered from the Reddit community, along with the two subscription-based sports streaming services. All videos are captured with the experimental setup mentioned in the previous subsection. We analyzed the captured data of an NBA game in December 2019, the NFL SuperBowl in February 2020, a UEFA playoff game in February 2020, and an NHL game in March 2020. All captured events are before

[3] `https://www.charlesproxy.com`
[4] `https://www.similarweb.com`

the global shutdown of sports events due to the COVID-19 pandemic in 2020. All captured network data, video streaming log, and player activities are available online [17]. We used the `traceroute` command to determine the geographic locations of streaming sessions. In general, UEFA events were streaming from European countries, while the NBA, NHL, and NFL events were streaming from North America. However, some of the FLS sites use CDNs, and we could not find their originating locations.

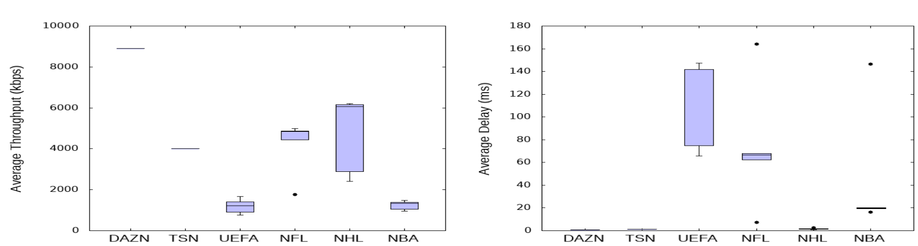
4 Measurement Results

To gain a comprehensive view of FLS, we evaluated video streaming from four different viewpoints, namely Network QoS, Video QoS, QUIC, and privacy.

4.1 Network Quality of Service (QoS) Analysis

Since most FLS providers record live events from a legitimate streaming service and broadcast them simultaneously [1], the quality of these services is unknown. In order to evaluate the network QoS provided by FLS Web sites, we analyze the packet-level traffic transferred during the streaming sessions.

Throughput. Several studies have proposed intelligent throughput-aware bitrate selection and adaptation algorithms for video players to improve the QoE in adaptive streaming techniques [32]. These algorithms predict the throughput and determine the bitrate for the next chunk of the video. High throughput variation could result in quality switches or stalls during the video playback [15]. Figure 2(a) shows boxplots of the average throughput for the FLS and legitimate providers. The legitimate sites had throughputs of 4-9 Mbps, compared to 1-6 Mbps for the FLS sites. The FLS throughputs were higher for the NFL and NHL sites, and lower for the UEFA and NBA sites. The FLS sites had problems during popular games, such as the 2019 NBA Finals, in which a Canadian team won the championship for the first time in NBA history. During this event, the FLS Web sites were not always able to deliver video, and some rejected new users with the message “Viewer limit reached”. Table 2 in the Appendix provides further details for each service provider, and time-series graphs of throughput are available on our project Web site [17].



(a) Throughput (b) Network delay

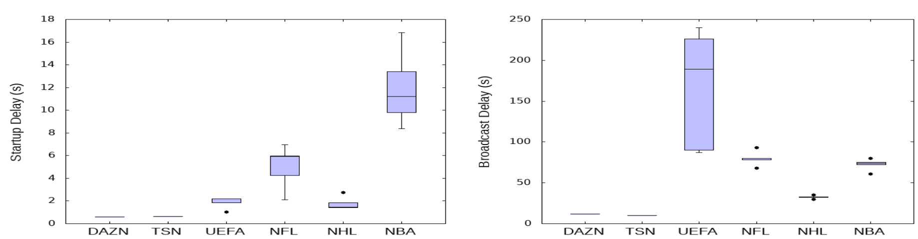
Fig. 2. Quality of Service (QoS) measurement results for live sports streaming sites

Delay. Network packet delay is an important performance characteristic of a computer network [3, 28]. We used ping to estimate the average delay of service providers. We set the ping packet size based on the average packet size of a video streaming session. We conducted the ping test during the games when the server was broadcasting and users were streaming. As shown in Figure 2(b), the average network delay for FLS sites tends to be much higher than the legitimate sites, and vary much more widely, though it does depend on their geographic location (e.g., some NHL streaming sites are in Calgary). Table 2 in the Appendix presents more detailed results for each service provider.
Packet Loss. We used the ping flood technique to study the packet loss. We observed that packet loss for the legitimate Web sites is about 0%, while it is between 1% and 4% for FLS providers. The higher loss can indicate problems in the network. Zennaro et al. [33] observed that packet loss below 1% is good, 1%-2.5% is acceptable, 2.5%-5% is poor, 5%-12% is very poor, and packet loss in excess of 12% is bad. Their observations showed that above 5% of packet loss, video conferencing becomes irritating and incomprehensible. The number of packet losses for each streaming site is shown in Table 2 in the Appendix.

4.2 Video Quality of Service (QoS) Analysis

In this section, we analyze the video QoS for our sports streaming Web sites.

Startup time. Startup time is the elapsed time between when the user requests a video stream and the start of playback. This metric includes network delays (e.g., RTT, DNS, CDN) and the initial buffering delay [9]. Previous studies have shown that startup time is important, though it has only a small impact on QoE [20, 34]. As shown in Figure 3(a), the legitimate Web sites start playing a video about 1 to 2 seconds faster than the FLS sites. We observed 8 to 16 seconds of startup delay when streaming from NBA FLS providers.



(a) Startup delay (b) Broadcast delay

Fig. 3. Quality of Experience (QoE) measurement results for live sports streaming sites

Broadcast delay. Broadcast delay is an intentional delay (often 7 seconds) inserted by live broadcasters to prevent mistakes or unacceptable content during live events. To calculate the real-time broadcast delay, we used information from two auxiliary Web sites to determine the actual time elapsed in a sports game: FlashScore.com and Bet365.com. FlashScore.com provides the fastest live and detailed stats of thousands of competitions in more than 30 sports, and Bet365 is one of the world's leading online gambling companies worldwide that covers over 30 different sports. As shown in Figure 3(b), DAZN had a broadcast delay of around 12 seconds for UEFA competitions. The FLS services that deliver UEFA games had between 1 and 4 minutes of broadcasting delay. This delay could be due to the time for recording and broadcasting the video. Due to the nature of live sports events, immediacy is extremely valuable. In general, live events streamed from FLS Web sites are not always truly "live" streams.

Some of the FLS Web sites, and in particular NHL aggregators, have a broadcasting delay around 30-35 seconds. By reviewing video player activities, we observed that these FLS services use channel providers like Wstream or Vimeo to deliver live streaming while recording videos. We also used the `traceroute` tool to locate the source of streaming, but found that these channel providers use CDNs like Akamai to deliver videos to users. Pandey et al. [24] also noted the use of Akamai CDNs by 4 of 12 illegal sports and news streaming providers studied. The most likely reason for using CDNs is to reduce latency for users.

Visual Quality. This metric indicates the average video resolution received by the video player, particularly when the streaming rate and quality level are dynamically adapted to the available bandwidth, such as in DASH (Dynamic Adaptive Streaming over HTTP) [31]. In our experiment, the two legitimate Web sites and several FLS Web sites (except NBA providers) provide HD video quality. However, we observed that the transferred data for the same duration of the same video streaming on a legitimate Web site is higher than the FLS Web sites.

Quality Switches. The number of quality changes is another video QoS factor that affects QoE [23]. The number of quality switches is calculated by counting the number of video resolution changes over the duration of the video session. We observed that 11 out of 20 FLS sites experienced two or more quality switches. We also found that a few FLS providers did not switch to lower resolution when video stalls occurred. We did not observe any quality switches in streaming from legitimate Web sites.

Stalls. Rebuffering is the most noticable streaming artifact for users [9]. If the player does not find sufficient new data in the buffer, it causes a pause during the playback that is called a *stall*. Studies show that the number of stalls has the highest impact on QoE [9]. From our (fast) campus network, our measurement tool never showed any stalls with legitimate sports streaming Web sites. Although all NHL FLS providers experienced quality switches, none of them stalled during video playback. However, the vast majority of the other FLS service providers suffered from several stalls. Table 3 in the Appendix shows the number of rebuffering events observed for each streaming site studied.

4.3 QUIC

TCP is the prevailing transport-layer protocol used by FLS services. TCP is amenable to video streaming, and is widely used for Web and mobile applications. For example, MPEG-DASH is an HTTP-based adaptive bitrate streaming technique to deliver high-quality streaming of media content over the Internet.

We observed that 18 out of 20 FLS Web sites deliver their services over TCP. One of the FLS providers used UDP and another one used the Datagram Transport Layer Security (DTLS) protocol to deliver video streaming. DTLS is similar to the TLS protocol that provides security guarantees over UDP. Interestingly, the two legitimate providers both deliver live streaming via UDP-based solutions. We observed that TSN delivers live video streams using QUIC [19].

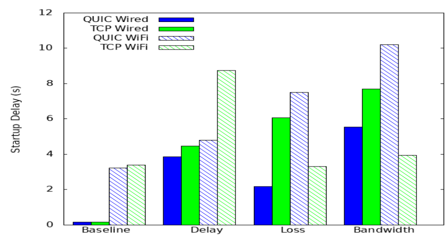
Experimental Setup. In this section, we describe our tests to evaluate the impact of QUIC on the performance of live streaming in different network settings. Google by default enables support for the QUIC protocol in the Chrome browser. To compare QUIC with TCP, we disable this feature in Chrome to stream live video over TCP. Although TCP Cubic is the default congestion control algorithm in QUIC [14], the congestion control algorithm used by QUIC version 50 on the TSN site was unknown to us. To test different network settings, we introduce delay, packet loss, and bandwidth limits by using the network emulation (netem) functionality of the traffic control (`tc`) Linux command. Metrics of interest are the startup delay, the average received throughput, and the number of quality switches.

We conducted all measurements on the described Linux PC with the Google Chrome browser for live streaming in both Wired and WiFi settings. Figure 4 shows selected results from our experiments, while the full results appear in Table 4 in the Appendix. The results report the averages from 10 video streaming sessions, from TSN provider, each lasting 100 seconds, with the browser's cache and history cleared before each session. We observed that all video streaming were streamed from the same IP address. Since recent studies show that QUIC provides minimal improvements for video streaming in networks with low delay and loss [2], we set high latency and loss to highlight the impacts of using QUIC.

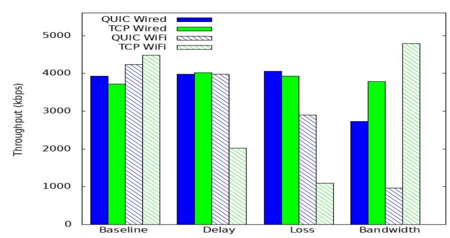
Network Type. Here we study the behavior of QUIC/TCP live video streaming in wired and WiFi networks. When the device is connected to a stable wired connection, enabling QUIC does not have an impact on startup time, but the average received throughput is slightly better than with TCP. When using the WiFi network, the QUIC protocol had a lower average startup time than TCP. However, the received throughput of video sessions using TCP was slightly higher than with the QUIC protocol.

Delay. We applied 500ms of delay to both wired and WiFi network connections. In this scenario, QUIC started playing the video with a lower startup delay than TCP over both wired and WiFi connections. The behavior of live streaming over

TCP in the WiFi network was significantly worse than QUIC, with higher startup time, much lower throughput, and more quality switches. This experiment shows that QUIC works better than TCP over the WiFi network with high delay.



(a) Startup delay



(b) Throughput

Fig. 4. QUIC vs TCP measurement results for live sports streaming sites

Loss. We added 25% random packet loss to both wired and WiFi connections. The packet loss drastically reduces the throughput in both QUIC and TCP live streaming. However, QUIC achieved a higher throughput. That is, QUIC was able to receive videos with higher resolution while TCP streamed with lower quality. This could be a key advantage of streaming via QUIC during popular games that induce network congestion and packet loss.

Bandwidth. We reduced the available network bandwidth to 8 Mbps. In this condition, the received throughput over TCP connections in both wired and WiFi networks are higher than the QUIC-based video streaming. The captured traces show that the server sends the data using three concurrent TCP connections on different ports, with the transferred data almost balanced over each connection. On the other hand, QUIC experienced worse performance in comparison to TCP. In the WiFi network with limited bandwidth, QUIC's startup time is higher, with lower received throughput, and more quality switches.

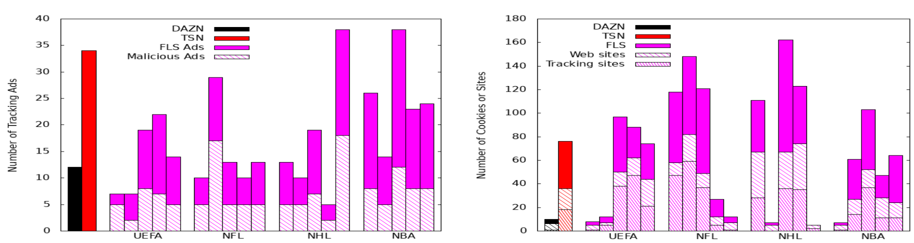
4.4 Privacy Analysis

The results from the Privacy View of FLS sports Web sites are summarized in Figure 5, as well as Table 5 in the Appendix. We discuss selected results next.

HTTP vs. HTTPS. While the two legitimate sports streaming sites deliver their services over HTTPS, most of the FLS sites use HTTP rather than HTTPS. There may be several reasons why FLS providers do not upgrade to HTTPS on their Web site, such as the costs to purchase and install SSL certificates on the server, the extra CPU processing required for encryption, and the fact that some FLS providers frequently change their Web domains. For these reasons, they may just simply opt to deliver their services over HTTP.

Ad and tracking services. To recognize advertisement and tracking services, we leveraged the EasyList and EasyPrivacy filter lists provided by the ad-blocker community. We used Privacy Badger[5] to distinguish malicious ads from other ads. By investigating the generated HTTP(S) requests/responses, we observed that both FLS and legitimate Web sites connect users to advertising and tracking services (see Figure 5(a)). However, the legitimate Web sites mostly connect to known tracking domains, such as Facebook and Google analytics, while the FLS sites expose users to malicious trackers like onclicksuper.com, which is known to redirect browsers to many unwanted advertisements. In addition, we observed that some tracking services like google-analytics.com appear in both FLS and legitimate sports streaming Web sites.

Overlay ads and offered applications. During the data collection phase, we observed that FLS Web sites use different techniques to show overlay and pop-up ads. Some of these overlay ads cover part of the video player, and trick users into pushing a fake close button, which then pops up multiple overlay ads. These ads violate the online advertising standards [12], degrade the video streaming QoE, and also lure users to numerous potentially malicious ads. Clicking on misleading ads can lead to computer viruses such as ransomware, trojans, crypto-mining, etc. In addition, we observed that some FLS Web sites offer a complimentary application to watch free live sport streams on the mobile device. Prior work has shown that these applications contain an advertising package, display ads without user consent, and trigger potential ad fraud [25].



(a) Advertisements (b) Cookies

Fig. 5. Privacy and security measurement results for live sports streaming sites

Browser security. Sandboxing is often used to run a Web browser in a low-permission mode that limits malware access to vulnerable aspects of the operating system. However, some users bypass these security warnings when accessing FLS sites [1]. Also, tools like ad-blockers can protect the user from deceptive ads linked to scams and malware [22]. However, some FLS providers use anti-ad-blocking techniques, or simply refuse to serve users with ad-blockers installed.

Cookies. We observed that both FLS and legitimate Web sites install third-party advertising and tracking cookies on user systems. Since cookies contain

[5] `https://www.privacybadger.org`

a history of the user's actions, they may be exploited or misused to track the user's behavior. Figure 5(b) shows the number of third-party cookies observed for each Web site in our dataset. For instance, we observed that visiting the TSN site results in 76 cookies from 38 different third-party Web sites, 18 of which are third-party tracking sites. Unlike TSN, DAZN alerts users about the use of cookies on its Web site, and installs a few cookies on user systems. In general, FLS Web sites trigger more advertising and tracking on user systems. In addition, some FLS Web sites set zombie cookies, which can automatically re-create themselves from stored data even after being deleted.

Data Leaks. By investigating POST requests, we observed that some FLS sites send user information such as IP address, ISP, city, area, device name, OS, browser version, and graphic card model to tracking Web sites. In addition, we discovered TSN uses a new approach, wherein a single POST method was used to perform multiple GET and POST requests. To do this, it inserts several GET and POST requests in a JSON-like format, and then sends all of these using one GET request to its server. One of the POST requests was 16,029 bytes long, and contained 18 GET and 3 POST requests, each addressing a tracking/advertisement service. This approach can hide requests from browsers, ad-blockers, and other security tools. An example of these POST requests is available on our project Web site [17].

5 Related Work

One early work that mentioned free live sports streaming was the epilogue of the *Globalization and Football* book [11], in which the authors discussed the impact of emerging FLS platforms on 'the global game'. Later, Birmingham et al. [4] studied FLS for England's Premier League of soccer, and noted parallels to the music industry, which faced similar piracy issues in the 1990s.

FLS services have grown tremendously over the past decade. Rafique et al. [25] explored the FLS ecosystem by investigating those infringing upon sports streaming Web sites. In addition, they analyzed the advertising content that the FLS Web sites expose during the live broadcasts.

Ayers et al. [1] offered a solution to automatically crawl and discover aggregator Web pages through the Google search engine. Then they studied FLS services by collecting and investigating 500 illegal live streaming domains. They observed that despite the improvement in the privacy mechanisms by ad-blockers and browsers, users are still using illegal streaming and exposing themselves to scams and deceptive ads. Kariyawasam et al. [16] studied the copyright concerns in the FLS ecosystem by analyzing the legal landscape for live sports streaming.

Bronzino et al. [5] developed models that derive video quality metrics from encrypted video streaming services. Biernacki et al. [3] conducted a thorough video streaming simulation study with different network conditions and video bitrates. Their study showed that QoS metrics significantly impact the QoE metrics for video streaming. In many cases, however, the buffering strategies implemented by a player client are able to mitigate unfavourable network conditions and further improve QoE.

The main novelty of our own work is the focus on performance tradeoffs in live sports streaming (i.e., QoS and QoE), as well as on user privacy and security. Furthermore, we provide multiple observational viewpoints at different layers of the protocol stack, using a customized version of the MoVIE tool.

6 Conclusion

In this paper, we presented a measurement study of FLS sites to identify tradeoffs in performance (i.e., network QoS and video QoS) as well as privacy and security. Our measurements were made using an extended version of an open-source video measurement tool called MoVIE [18]. We also conducted measurements of two legitimate sports streaming Web sites to provide a basis for comparison.

Our main results can be summarized as follows. We observed a long broadcasting delay in free live streams. The throughput, streaming quality, and packet loss rate differ greatly across FLS sites. TSN delivers live video streaming using QUIC. We observed that QUIC's benefits are larger in WiFi networks with higher delay and loss. Similar to previous studies, we also noted that the FLS ecosystem continues to flourish. Although FLS is free, you always "get what you pay for": the user pays the cost of FLS by dealing with the uncertainty of the streaming services, and the inherent privacy/security risks.

Ethical Considerations

There are several ethical issues associated with studying illegal FLS services. First, many countries have Fair Dealing exceptions that authorize the use of copyrighted materials for specific purposes. In Canada, these purposes include "research, private study, education, parody, satire, criticism, review, or news reporting". Second, we studied Web sites that millions of users visit monthly, despite the copyright law and potential malicious behaviours. We do not crawl automatically through the FLS providers, and our study has minimal impact on visit numbers. In addition, there is a chance that any increased views triggered by our study will be suitably moderated by the increased awareness of FLS users. Finally, to study privacy issues, it was necessary to decrypt the device's network traffic to see the incoming and outgoing flows. However, our measurements and experiments were conducted on a single device in a controlled lab environment. We collected neither personal data nor the device traffic from other users. All captured data are publicly available for future studies [17].

Appendix

The following four tables provide the detailed results from our active and passive measurement experiments with live sports streaming sites. In Table 2, Table 3, and Table 5, the rows correspond to the different legitimate and FLS providers studied, while the columns represent different performance metrics for network QoS, video QoS, and privacy, respectively. Table 4 provides results for the QUIC experiments, which structurally differ from the other measurement results.

Table 2. Network Quality of Service (QoS) metrics for live sports streaming Web sites.

Type		Provider	HTTP(S)	Protocol	Avg Throughput	Trace SYN RTT	Trace Loss		TCP Retrans	Ping Avg RTT	Ping SD Delay	Ping Loss
							%	pkts				
Paid	UEFA NFL	DAZN	HTTPS	UDP	8,899 kbps	-	-	-	-	1.046 ms	0.975 ms	0%
	NHL NBA	TSN	HTTPS	QUIC	4,021 kbps	-	-	-	-	1.252 ms	1.119 ms	0%
FLS	UEFA	P1	HTTP	TCP	1,676 kbps	59.061 ms	0.8%	114	69 pkts	65.544 ms	7.439 ms	2%
		P2	HTTP	TCP	1,212 kbps	137.900 ms	0.8%	75	24 pkts	141.688 ms	12.368 ms	3%
		P3	HTTP	TCP	918 kbps	135.949 ms	0.7%	49	29 pkts	141.759 ms	31.675 ms	2%
		P4	HTTP	UDP	1,413 kbps	-	-	-	-	74.548 ms	16.54 ms	2%
		P5	HTTP	TCP	766 kbps	155.932 ms	0.9%	74	40 pkts	147.422 ms	46.860 ms	4%
	NFL	P6	HTTP	TCP	4,833 kbps	53.793 ms	0.0%	11	11 pkts	66.500 ms	12.062 ms	7%
		P7	HTTP	TCP	1,763 kbps	145.940 ms	0.1%	16	12 pkts	164.126 ms	38.925 ms	0%
		P8	HTTP	TCP	4,990 kbps	150.393 ms	0.1%	105	43 pkts	62.496 ms	7.896 ms	0%
		P9	HTTP	TCP	4,428 kbps	179.007 ms	0.1%	53	46 pkts	67.876 ms	12.212 ms	4%
		P10	HTTP	TCP	4,877 kbps	7.248 ms	0.0%	23	26 pkts	7.351 ms	7.440 ms	0%
	NHL	P11	HTTP	UDP	2,412 kbps	-	-	-	-	1.359 ms	1.476 ms	0%
		P12	HTTP	TCP	2,888 kbps	-	0.0%	12	26 pkts	1.570 ms	1.612 ms	0%
		P13	HTTP	TCP	6,195 kbps	15.331 ms	0.0%	3	10 pkts	2.597 ms	2.661 ms	0%
		P14	HTTP	TCP	6,168 kbps	-	0.0%	17	10 pkts	0.943 ms	0.845 ms	0%
		P15	HTTP	TCP	6,073 kbps	7.923 ms	0.0%	11	18 pkts	1.160 ms	1.256 ms	0%
	NBA	P16	HTTP	TCP	1,380 kbps	47.015 ms	0.1%	25	21 pkts	19.739 ms	1.195 ms	0%
		P17	HTTP	TCP	1,481 kbps	10.748 ms	0.1%	50	60 pkts	19.495 ms	0.557 ms	0%
		P18	HTTP	TCP	1,332 kbps	21.159 ms	0.0%	16	18 pkts	20.216 ms	0.748 ms	0%
		P19	HTTPS	TCP	1,050 kbps	311.496 ms	0.0%	11	25 pkts	146.680 ms	3.192 ms	0%
		P20	HTTP	TCP	960 kbps	28.848 ms	0.1%	17	22 pkts	16.482 ms	2.164 ms	0%

Table 3. Video QoS metrics for live sports streaming Web sites.

Type	Sports	Provider	Startup Time	Resolution	Rebuffering	Quality Switches	Broadcast Delay
Paid	UEFA NFL	DAZN	0.62 s	1280 × 720	0	0	12 s
	NHL NBA	TSN	0.64 s	1280 × 720	0	0	10 s
FLS	UEFA	P1	2.21 s	1280 × 720	2	0	87 s
		P2	2.17 s	1280 × 720	1	0	189 s
		P3	1.02 s	1280 × 720	4	0	90 s
		P4	1.83 s	960 × 540	0	0	226 s
		P5	2.18 s	1280 × 720	4	0	240 s
	NFL	P6	2.11 s	1024 × 576	5	0	93 s
		P7	4.24 s	1280 × 720	0	0	78 s
		P8	6.97 s	1024 × 576	3	0	80 s
		P9	5.91 s	1024 × 576	3	0	78 s
		P10	5.97 s	896 × 504	0	3	68 s
	NHL	P11	2.75 s	1280 × 720	0	2	32 s
		P12	1.44 s	1280 × 720	0	2	30 s
		P13	1.40 s	1280 × 720	0	2	32 s
		P14	1.43 s	1280 × 720	0	3	33 s
		P15	1.83 s	1280 × 720	0	2	35 s
	NBA	P16	8.39 s	640 × 360	6	5	74 s
		P17	16.82 s	986 × 504	4	4	80 s
		P18	9.81 s	640 × 360	8	4	75 s
		P19	11.21 s	512 × 288	6	2	72 s
		P20	13.40 s	512 × 288	7	2	61 s

Table 4. Comparison of QUIC and TCP in network emulation experiments.

Network Setting		QUIC			TCP		
Limitation	Type	Startup time (s)	Throughput	Quality Switch	Startup time (s)	Throughput	Quality Switch
None	Wired	0.169	3925 kbps	0	0.161	3720 kbps	0
	WiFi	3.233	4239 kbps	0	3.4054	4475 kbps	0
Delay= 500 ms	Wired	3.8624	3982 kbps	1	4.4692	4018 kbps	1
	WiFi	4.800	3978 kbps	3	8.755	2026 kbps	5
Loss Rate= 25%	Wired	2.189	4058 kbps	1	6.082	3928 kbps	2
	WiFi	7.514	2892 kbps	1	3.324	1095 kbps	0
Bandwidth = 8 Mbps	Wired	5.545	2734 kbps	2	7.686	3789 kbps	1
	WiFi	10.213	970 kbps	2	3.939	4789 kbps	0

Table 5. Privacy view of live sports streaming Web sites.

Type	Sports	Provider	Tracking ad	Malicious ad	Offering apps	Encryption Scheme	Anti ad-blocker	Cookie Consent	# 3rd-party cookies	# 3rd-party Web sites set cookies	# 3rd-party tracker sites set cookies
Paid	UEFA NFL	DAZN	12	0	No	CENC	No	Yes	10	6	1
	NHL NBA	TSN	34	0	No	CENC	No	No	76	36	18
FLS	UEFA	P1	7	5	Yes	N/A	No	No	8	5	1
		P2	7	2	No	N/A	No	No	12	7	5
		P3	19	8	Yes	N/A	No	No	97	50	38
		P4	22	7	No	N/A	No	No	88	62	47
		P5	14	5	No	N/A	No	No	74	44	21
	NFL	P6	10	5	No	N/A	No	No	118	58	47
		P7	29	17	Yes	N/A	No	Yes	148	82	59
		P8	13	5	No	N/A	No	Yes	121	49	37
		P9	10	5	No	N/A	No	No	27	12	5
		P10	13	5	No	N/A	No	No	12	7	1
	NHL	P11	13	5	No	N/A	No	No	111	67	28
		P12	10	5	No	N/A	No	No	7	5	0
		P13	19	7	Yes	N/A	Yes	Yes	162	67	36
		P14	5	2	No	N/A	No	No	123	74	35
		P15	38	18	Yes	N/A	No	No	5	5	2
	NBA	P16	26	8	Yes	N/A	No	No	7	5	1
		P17	14	5	Yes	N/A	Yes	No	61	27	14
		P18	38	12	Yes	N/A	No	Yes	103	52	37
		P19	23	8	Yes	N/A	No	No	47	28	11
		P20	24	8	Yes	N/A	No	No	64	24	11

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Acknowledgements

The authors thank the PAM 2021 reviewers and shepherd David Choffnes for their feedback and suggestions. Financial support for this research was provided by Canada's Natural Sciences and Engineering Research Council (NSERC).