Be Daring to Push your Ads Forward: Measuring the (Over)use of Service Workers for Advertising Purposes

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Abstract. Rich offline experience, periodic background sync, push notification functionality, network requests control, improved performance via requests caching are only few of the functionalities provided by the Service Workers API. This new technology, supported by all major browsers, can significantly improve users’ experience by providing the publisher with the technical foundations that would normally require a native application. Albeit the capabilities of this new technique and its important role in the ecosystem of Progressive Web Apps (PWAs), it is still unclear what is their actual purpose on the web, and how publishers leverage the provided functionality in their web applications.

In this study, we shed light in the real world deployment of Service Workers, by conducting the first large scale analysis of the prevalence of Service Workers in the wild. We see that Service Workers are becoming more and more popular, with the adoption increased by 26% only within the last 5 months. Surprisingly, besides their fruitful capabilities, we see that Service Workers are being mostly used for Push Advertising, in 65.08% of the Service Workers that connect with 3rd parties. We highlight that this is a relatively new way for advertisers to bypass ad-blockers and render ads on the user’s displays natively.

1 Introduction

The proliferation of, and our ever-increasing reliance on, the Web have boosted the development of more complex and user-friendly Web applications that can operate cross-platform (on both desktop and mobile Web). Recent advancements in the contemporary browsers and in the availability of technologies like the Service Worker API have 1) enabled users to receive timely updates via push notifications, 2) their content synced on the background, 3) improved performance (via request caching) and 4) even allowed to work offline.

These rich capabilities of Service Workers played an important role in the birth and growth of a whole separate type of application software called Progressive Web Apps (PWAs) [1]. PWAs are built on top of three requirements: HTTPS, Service Workers and a web app manifest. By combining functionalities of different web APIs (e.g., WebRTC, Cache API, Push API), PWAs are capable
of providing the benefits of both native apps and websites worlds: reliability, rich user experience, and multi-platform support via a single codebase [2].

The somewhat revolutionary functionality of Service Workers could not avoid drawing the attention of the academic community with regards to its security aspects. Specifically, research studies have shown that this technology provides rich capabilities not only to users and web developers, but to potential attackers as well. In [3], authors present a framework that exploits Service Workers functionality to launch attacks like DDoS, cryptojacking and distributed password cracking. In [4], authors investigate the potential privacy leaks that malicious Service Workers can cause on a victim’s browser.

Notwithstanding the important research on the Service Worker API, yet it is still unknown what is the prevalence and the growth of the Service Worker deployment across the Web, but also how publishers leverage the provided functionality of Service Workers in their Web applications. In this study, we aim to address these exact questions, by conducting a full-scale analysis of Service Workers (the core component of PWAs) in the wild. Specifically, we crawl a large number of websites to detect the deployment of Service Workers, we monitor and characterize their communications across the Internet, and investigate their purpose of existence and operation on the websites they were found.

In summary, the contributions of our present work are:

1. By crawling the top 150K sites of the Tranco list, we detect a dataset of 7,444 Service Workers-registering websites. The same crawl after 5 months reveals a high increase (26%) in the adoption of Service Workers.
2. We use Wayback Machine to go back in time and find that, from 2015 till today, there were 1.62× more publishers per year, on average, utilizing Service Workers in their web applications.
3. By analysing our collected dataset, we conduct the first full-scale study of the Service Workers deployment on the web. Specifically, we investigate with whom the deployed Service Workers communicate over the Internet, what are the websites that use such technology the most, as well as what is the purpose of the deployed Service Workers. Surprisingly, we see that despite the important functionality of Service Workers (e.g., timely notifications, background sync, etc.), yet a stunning 65.08% of the Service Workers that connect with 3rd parties use Service Workers for pushing ads to the users, under the radar of possibly deployed ad-blockers (51% of such ads have even been flagged as malicious [5]).

2 Service Workers

A Service Worker is a JavaScript script that runs separately from the main browser thread, and can intercept network requests, perform caching or retrieving resources from the cache, and deliver push messages. Service Workers are independent from the Web application they are associated with, so they cannot access the DOM directly. Service Workers are non-blocking and fully asynchronous. Therefore, synchronous XHR and localStorage cannot be
used inside a Service Worker. A Service Worker can import and execute 3rd party scripts within its context, and receive push messages from a remote server, thus letting the associated website push notifications to the user (even when the website is not open in a browser tab). A Service Worker can be registered to the browser via the `serviceWorkerContainer.register()` or `navigator.serviceWorker.register()` function, which take as argument the (HTTPS only) URL of the remote JavaScript file that contains the worker’s script. This URL is passed to the internal browser’s engine and is fetched from there. For security purposes, this JavaScript file can be fetched only from the first-party domain, i.e., cannot be hosted by a CDN or a 3rd party server.

## 2.1 Web Push Notifications

The Web Push API gives web applications the ability to receive messages pushed from a remote server, whether or not the Web app is in the foreground, or even loaded in a browser tab. The Web Push API enables developers to deliver asynchronous notifications and updates to (desktop or mobile) users that opt-in, resulting in better engagement with timely new content. For an app to receive push messages, it has to have an active Service Worker and subscribe to push notifications (each subscription is unique to a Service Worker). The endpoint for the subscription is a unique capability URL, and the knowledge of the endpoint is all that is necessary to send a message to the application’s users. Therefore, the endpoint URL needs to be kept secret or anyone might be able to send push messages to the app’s users.

## 2.2 Push Advertising

Web push notification technology itself is nothing new, but it has started to be used for advertising purposes very recently. In fact, push marketing skyrocketed at the end of 2018. Push ads are a type of native ad format in the form of a notification message from a website, which appears on the user’s screen on top of other windows. Users who click on those messages get redirected to the advertiser’s landing page, thus, generating ad-conversion.

The push ad delivery is cross-platform and aims to offer an opt-in based, highly engaging way for advertisers to reconnect and expand their audiences, while at the same time it achieves higher click-through and conversion rates than other ad formats [6]. A push notification usually consists of: (i) the main image which conveys the sense of the ad impression, (ii) the small icon which explains the main image, (iii) the headline which is the main element to engage users and (iv) the message text that shows the main details of the offer. Contrary to traditional programmatic advertising [7,8,9], in push ads, advertisers pay for clicks (i.e., Cost-Per-Click) and not for impressions (i.e., Cost-per-Impression). The minimum cost per click starts from $0.0104 [10], when in Real-Time Bidding the median cost per impression has been measured to be as low as $0.0025 [11].
Fig. 1: High level overview of how Service Workers deliver push ads on the user display even with ad blocker deployed.

3 Use Case

In Figure 1, we present a high level overview of how Service Workers and push notifications work. As we can see, first (step 1), the user visits a website they are interested in, thus instructing a browser to connect with a web server (step 2) that responds back with the webpage’s HTML/CSS/JavaScript resources, along with a Service Worker script, which gets registered (step 3). This snippet will deploy a Service Worker inside the user’s browser (step 4) which operates independently from the rendered website. Then, the Service Worker will ask the user’s permission to push notification massages on their display (step 5) and if granted, it will establish a communication channel with a remote messaging platform to subscribe to their push notifications (step 6). Whenever the message publishing entity (e.g., news update feed server, article recommendation server, ad server) behind the messaging platform has updates to push to the website’s users, it uploads them to the platform which will push them to all subscribed users (step 7). On the user’s end, upon message arrival, the deployed Service Worker creates a push notification with the received message on the user’s display (step 8). As shown, a Service Worker may establish a separate communication channel with a remote messaging platform that cannot be monitored or filtered by any potentially deployed ad-blocking browser extension. This means that whenever a user opts-in to receive updates from a website, they may start receiving ad notifications instead, even if they have an ad-blocker deployed.
Table 1: Summary of our dataset

| Data                                                   | Volume       |
|--------------------------------------------------------|--------------|
| Sites parsed                                           | 150K         |
| *(1st crawl)* Sites registering a Service Worker (SW)  | 7,444 (4.96%)|
| SWs that do not communicate with any remote server     | 336 (4.51%)  |
| SWs communicating only with the first party            | 2,054 (27.59%)|
| SWs communicating with at least one 3rd party          | 5,054 (67.89%)|
| SWs communicating with at least one ad server          | 3,289 (44.18%)|
| SWs communicating with at least one analytics server   | 164 (3.24%)  |
| *(2nd crawl)* Sites registering a SW                   | 9,383 (6.25%)|

4 Data Collection

Crawling infrastructure. After manual inspection, we see that there are websites checking first if the site has push notification permissions, before registering Service Workers. This means that in order to perform a large scale crawl of websites and detect the deployment of Service Workers, and the use of push notifications, some sort of automation for the notification consent is required. To address this, we leverage the crawler presented in [5]. This crawler creates docker containers with fresh instrumented Chromium browser instances and browser automation scripts. The browser has the `RequestPermission` and `PermissionDecided` methods of the class `Permission-ContextBase`, modified to automatically grant permissions on every site. Then, a custom Puppeteer [12] script listening to `serviceworkercreated` event is used to log when a Service Worker is registered by a website, the page that registered this Service Worker and the URI of the source code. As soon as a Service Worker is registered, it can subscribe for push notifications via a Cloud Messaging Platform (e.g., Firebase Cloud Messaging [13]) with an API key passed from the server to the browser, which is also logged by listening for `PushManager.subscribe` events. Then, the custom Puppeteer script logs the communication between the Service Worker and the Web.

Creating the Dataset. We create a dataset of websites that utilize Service Workers, by crawling the landing pages of the 150K top sites of a (deduplicated, pay-level only domains) Tranco list [14] in December 2020. Each site is visited for three minutes, during which, and according to our experiments, is sufficient for a Service Worker to be register and make the first touch with the corresponding server(s) *(1st crawl)*. After 5 months (April 2021), we revisit the websites of our initial Tranco list to inspect how the ecosystem evolved, i.e., sites dropping Service Workers, new sites adopting Service Workers *(2nd crawl)*. A summary of the collected data is in Table 1.

Data analysis. To classify the network traffic of the registered Service Workers in our data, we use the 1Host filterlist [15] and flag the ad-related domains in our weblogs. Additionally, we used SimilarWeb [16] to categorize the sites registering Service Worker based on the content they deliver.
Fig. 2: Top content categories of sites using (i) Service Workers (blue) and (ii) Service Workers that communicate with advertisers (red). As we can see, Service Workers is a technique widely used in sites delivering content related to ‘News and Media’ and ‘Computers Electronics and Technology’.

**Historical analysis and static detection.** To explore the evolution of Service Workers across time, we use our data of Service Worker-registering sites to extract heuristics and keywords that indicate the registration or use of Service Workers. This way, we develop a crawler that can statically detect the registration of Service Workers in these specific set of sites. Next, we use Wayback Machine [17], and specifically waybackpy Python package [18] to go back in time and find the day that these websites started deploying Service Workers on their visitors’ browsers.

**Ethical Considerations.** It is important to note that during the conduct of this study, we neither gathered or used any user data, nor impeded or tampered with the proper operation of the sites we crawled, in any way. Our research was purely limited in passively monitoring the behavior of Service Workers.

5 Measurements

**What are the kind of sites deploying Service Workers?** By crawling the top 150K websites of the Tranco list, we find that 7,444 (4.96%) of these sites register one or more Service Workers on the users’ browser (Table 1). To understand what sites deploy such a technique, we query Similarweb [19] for the content category of each of our sites and we get a response for 86.7% of them. In Figure 2 we plot the top 15 categories. We see that the sites that mostly use Service Workers (in blue) are related to ‘News and Media’ (22.05%), with the categories of ‘Computers Electronics and Technology’ and ‘Arts and Entertainment’ following (6.27% and 3.5%, respectively).
Fig. 3: Growth factor of the Service Workers deployment in our dataset. From 2015 till mid 2021, there are $1.62 \times$ more publishers per year, on average, utilizing Service Workers in their Web apps.

Prevalence of Service Worker deployment. By revisiting the sites of the same Tranco list after 5 months (as described in Sec. 4) via the same crawler, we found a total of 9,383 websites registering a Service Worker (6.25% of the total sites crawled), which indicates a 26% increase. More specifically, we found 1) 6,173 websites using Service Workers in both crawls, 2) 1,271 websites that stopped using them at some time after our 1st crawl, and 3) 3,210 new websites deploying them in their visitors’ browsers.

This rapid growth in the prevalence of Service Workers within just 5 months, motivated us to go back in time and observe their evolution across the years. Specifically, by using Wayback Machine web archive and our initial set of Service Worker-registering websites, we crawled previous versions of their landing pages to spot when they started using Service Workers. As a result, we crawled all the way back to 2015, when the first websites in our dataset started using Service Workers. As seen in Figure 3 after 2015, every year we observe an average growth factor of 1.62. In 2017 and 2018 we see this growth increasing with $2.09 \times$ and $2.14 \times$ more websites deploying Service Workers than the previous year, respectively.

Communications between Service Workers and Web. Next, by analyzing the traffic that the registered Service Workers generate, we see that 27.59% communicate only with the first party, when 67.89% of them communicate with at least one 3rd party and 4.51% of them do not communicate with the Web at all (Table 1). In Figure 4, we plot (in blue) the number of distinct 3rd parties each registered Service Worker in our dataset communicates with. As we can see, 32.1% of the Service Workers communicate with no 3rd party (as mentioned: 27.59% connects with the first party only, and 4.51% with no one), when the majority (51.6%) communicates with exactly one 3rd party, proving that there are specific agreements between publishers and 3rd party advertisers, analytics,
content or library providers. It is important to note that there is a significant 16.3% communicating with 2 or more (even 26!) distinct 3rd parties.

**Service Workers and Push Advertising.** By using the popular filter-list of 1Hosts, we classify the type of domains the Service Workers connect with in our dataset. Surprisingly, as we see in Figure 5, in essence 3rd party communications of Service Workers are used for advertising, since the majority (65.08%) of the Service Workers that connect with 3rd parties, establish these connections to receive content from at least one push advertiser (9.51% receive content from 2 advertisers or more). On the contrary, only 34.92% of the Service Workers perform at least one request to 3rd parties, but communicate with zero ad servers.

**The popularity of sites leveraging Push Advertising.** In Figure 6 we plot the popularity rank of the websites that deploy Service Workers on the users’ side. As we see, the sites that tend to deploy ad pushing Service Workers are of lower popularity ranks in comparison to the ones that use Service Worker only locally, without connecting to any remote server. Specifically, the median site that registers Service Worker that does not connect with any remote server has a popularity rank of around 40000 in Tranco (grey). On the other hand, the median site with Service Worker that connects (i) only with first party domains, or with 3rd parties that do not include ads is around 50000 rank (green or orange) (ii) with push ad domains around 60000 rank (red).

Also, as we see in Figure 3 the content categories of the sites with Service Workers that communicate with ad servers (in red) are topped by ‘News and Media’ (27%), ‘Computers, Electronics and Technology’(6.42%) and ‘Adult’ (4.79%). This is somewhat expected, since ‘News and Media’ sites have higher
chances to convince a user to give their consent to receive timely news updates via push notifications, that can also include ads.

In Figure 7 we focus on the websites that use Service Workers to communicate with 3rd parties. Although Figure 2 shows the most types of websites which dominate the world of Service Workers, Figure 7 shows which of those types are more eager to use Service Workers for advertisement. We see that Soccer sites lead this effort, with a percentage close to 85%. This means that from the Soccer sites which use Service Workers to communicate with 3rd parties, 85% use the Service Workers to communicate with at least one ad server. The ‘Animation and Comics’ follow closely with 84% and ‘File Sharing and Hosting’ are next, with 83.78%. The ‘News and Media’ are in the fifth place with a bit more than 77%. At this point we should take a step back and reflect on these numbers. These are pretty high percentages. They suggest that 75% or 80% of these websites use Service Workers for advertisement. One can not help but wonder why were Service Workers invented in the first place. It is true that several people may argue that Service Workers were invented to provide offline operation, synchronize data in the background, and retrieve updates. However, we see a different picture here: Service Workers that communicate with 3rd parties are primarily used for advertisements. It seems that advertisers have found a new way to reach our desktop: a way invented for a different purpose. And as if this is not enough, this way can not be controlled (or filtered out) by Web end-users, e.g., through ad-blockers. One can only smile in melancholy at the Google Developers
guide advising: “Whatever you do, do not use notifications for advertising of any kind.”

The dominant Push Ad Networks. In Figure 8, we plot the top 10 most popular Push Ad Networks in our data, and the portion of the registered Service Workers they communicate with. We see that onesignal.com dominates push advertising by owning more than 37.49% of the market, with the majority of the rest Push Ad Networks owning less than 4% each. In Figure 9, we plot the distribution of all push ad networks in our dataset along with the sites they deliver push ads to. We can see that the distribution can be modeled by two straight lines for large numbers in the x-axis, indicating that the distribution has a piece-wise power-law tail. We can also see the head representing the major player onesignal.com.

6 Related Work

The powerful technology of Service workers provides rich functionality to developers and has triggered an important body of research around its security and privacy aspects.

Papadopoulos et al. in \(^3\) are the first to study Service Workers in an attempt to raise awareness regarding a new class of attacks that exploit this exact HTML 5 functionality. Specifically, the authors investigated the potential security vulnerabilities of Service Workers and they demonstrated multiple attack scenarios from cryptojacking to malicious computations (e.g., distributed password cracking), as well as Distributed Denial of Service attacks.

\(^3\) https://developers.google.com/web/ilt/pwa/introduction-to-push-notifications
Karami et al. in [4] studied attacks that aim to exploit Service Workers vulnerabilities to ex-filtrate important privacy information from the user. Specifically, they demonstrated two history-sniffing attacks that exploit the lack of appropriate isolation in these browsers including a non-destructive cache-based version. Finally, the authors proposed a countermeasure and developed a tool that streamlines its deployment, thus facilitating adoption at a large scale.

Chinprutthiwong et al. in [19] described a novel Service Worker-based Cross-Site Scripting (SW-XSS) attack inside a Service Worker, that allows an attacker to obtain and leverage Service Worker privileges. Additionally, they developed a SW Scanner to analyze top websites in the wild, and they found 40 websites vulnerable to this attack including several popular and high ranking websites. Squarcina et al. in [20] demonstrated how a traditional XSS attack can abuse the Cache API of a Service Worker to escalate into a person-in-the-middle attack against cached content, thus, compromising its confidentiality and integrity.

Subramani et al. in [5] proposed PushAdMiner: a new tool to detect Web Push Notifications (WPNs) on the web. The authors collected and analyzed 21,541 WPN messages and 572 WPN ad campaigns, for a total of 5,143 WPN-based ads when 51% of all them were malicious.

Finally, Lee et al. in [21] conducted a systematic study of the security and privacy aspects of PWAs. The authors demonstrated a cryptojacking and a browser history exfiltration attack, before they suggested possible mitigations against the vulnerabilities of PWAs and their corresponding Service Workers.

7 Summary & Conclusion

In this paper, we set out to explore the ecosystem of Service Workers and how websites overuse them to deliver ads (even when user has deployed ad-blockers).
We analyzed the top 150K websites of the Tranco list and our findings can be summarized as follows:

1. A non-trivial percentage (4.96%) of sites deploy a Service Worker on the user side.
2. Within the last 5 months, there has been a 26% increase in the adoption of Service Workers.
3. Overall, by using Wayback Machine, we found that from 2015 till today, there were 1.62× more publishers per year, on average, utilizing Service Workers in their web applications.
4. 32.1% of the Service Workers communicate with no 3rd party (27.59% connects with its first party only and 4.51% connects with nobody). The majority (51.6%) communicates with exactly one 3rd party with a significant 16.3% communicating with 2 or more (and up to 26) distinct 3rd parties.
5. Third-party communications are mostly for pushing ads: **A stunning 65.08% of the registered Service Workers that communicates with 3rd party servers, communicate with at least one advertiser.**
6. Most of the ads-pushing Service Workers are deployed on ‘News and Media’ related sites (27%), with the ‘Computers, Electronics and Technology’ (6.42%), and ‘Adult’ (4.79%) related sites following.
7. For some website categories such as ‘Soccer’ and ‘File Sharing’, the percentage of ads-pushing Service Workers reaches as high as 85%.

Our study of Service Workers has revealed several surprising results with respect to the use of Service Workers on Web applications and websites. Future research could look into leakage of user personal information and tracking from Service Workers, as well as how ad-blockers can be revamped to still provide effective ad-filtering to their end-users.

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