Turning the Tide on Dark Pools?
Towards Multi-Stakeholder Vulnerability Notifications in the Ad-Tech Supply Chain

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***Abstract*—Online advertising relies on a complex and opaque supply chain that involves multiple stakeholders, including advertisers, publishers, and ad-networks, each with distinct and sometimes conflicting incentives. Recent research has demonstrated the existence of ad-tech supply chain vulnerabilities such as dark pooling, where low-quality publishers bundle their ad inventory with higher-quality ones to mislead advertisers. We investigate the effectiveness of vulnerability notification campaigns aimed at mitigating dark pooling. Prior research on vulnerability notifications has primarily focused on single-stakeholder scenarios, and it is unclear whether vulnerability notifications can be effective in the multi-stakeholder ad-tech supply chain. We implement an automated vulnerability notification pipeline to systematically evaluate the responsiveness of various stakeholders, including publishers, ad-networks, and advertisers to vulnerability notifications by academics and activists. Our nine-month long multi-stakeholder notification study shows that notifications are an effective method for reducing dark pooling vulnerabilities in the online advertising ecosystem, especially when targeted towards ad-networks. Further, the sender reputation does not impact responses to notifications from activists and academics in a statistically different way. In addition to being the first notification study targeting the online advertising ecosystem, we are also the first to study multi-stakeholder context in vulnerability notifications.**

1. Introduction

Fraud is rampant in the online advertising supply chain. In 2023, marketers globally spent more than 300 billion dollars on online advertising [1]. But nearly a quarter of this ad spend is lost to ad fraud [2]. Ad fraud generally takes one of three forms: inorganic or fraudulent interactions with ad content [3]–[5], manipulating conversion attribution [6], [7], and ad inventory laundering [8]–[11]. While the vulnerabilities exploited by each form of ad fraud are multifaceted, they generally exploit the complexity and opacity of the online advertising supply chain [12]. *This paper focuses on an emerging type of ad inventory laundering called dark pooling*. At a high-level, dark pooling allows low-quality (i.e., brand-unsafe) publishers make their ad inventory indistinguishable, to advertisers or brands, from the ad inventory of higher-quality publishers. Recent work [8] has shown that dark pooling is widespread and helps fund low-quality websites known for publishing misinformation and other brand-unsafe content.

Current strategies for mitigating dark pooling are ineffective. Solutions to prevent the laundering of low-quality ad inventory facilitated by dark pooling generally take the form of new standards for improving transparency and facilitating inventory verification in the online advertising supply chain. For instance, the Interactive Advertising Bureau (IAB) introduced standards such as `ads.txt` [13], `sellers.json` [14], `ads.cert` [15], and the Supply Chain Object [16] to help mitigate this type of ad fraud. Unfortunately, prior research consistently shows that entities do not comply with these standards [8], [17]–[20]. Consequently, these measures fail to mitigate, or even detect, ad inventory fraud. Further, given the largely self-regulated nature of the ad-tech ecosystem, we cannot expect significant improvements in compliance rates [21]–[23]. Therefore, it is important to explore alternative approaches to mitigate ad inventory fraud. *This paper examines the effectiveness of a different tactic, previously unused in the ad-tech supply chain: a vulnerability notification campaign*. Specifically, we examine the effectiveness of notification campaigns in mitigating dark pooling.

Findings from prior vulnerability notification research are unlikely to carry over to the online advertising supply chain. Running vulnerability notification campaigns to address security vulnerabilities is not a new idea. In the context of the Web, researchers have conducted many studies on how different notification campaign strategies affect the resolution of various vulnerabilities observed in online services [24]–[31]. Generally, these studies show that well-designed notifications can effectively resolve online vulnerabilities when successfully delivered to their targets. These prior studies typically focus on single-stakeholder scenarios — i.e., researchers sent vulnerability notifications to an entity that is capable of resolving the issue (e.g., a website operator) and monitored that entity's actions. However, this approach and its findings may not apply to the more complex multi-stakeholder ad-tech supply chain. In the ad-tech multi-stakeholder context: (1) vulnerability resolution may require cooperation from multiple independent entities (e.g., publishers, ad-networks, and advertisers); (2) it is unlikely for any one entity to have complete visibility into the supply chain; and (3) incentives of the independent entities may be different and at odds with each. These differences between single- and multi-stakeholder scenarios necessitate evaluating the effectiveness of notification campaigns for the latter. *Our work fills this gap by applying (and evaluating) lessons learned from the single-stakeholder context to the multi-stakeholder ad-tech supply chain context.*

Developing a vulnerability notification campaign for the ad-tech supply chain is non-trivial. Our research addresses several challenges related to the opacity of the ad-tech supply chain and the multi-stakeholder setting. First, we need to automate the detection of dark pooling vulnerabilities to conduct notifications at a reasonable scale. We address this challenge using methods from prior research [8] to identify dark pooling and the specific entities involved, such as publishers, ad-networks, and advertisers. Second, we must tailor our notifications to make them understandable and useful to each type of stakeholder. We accomplish this by designing notifications that provide entity-specific information, including high-level descriptions of the detected dark pooling vulnerability, technical evidence, and potential remedial actions. Finally, we need to assess the effectiveness of our notifications with statistical rigor and correctly attribute vulnerability resolutions to different stakeholders. We achieve this by conducting our study over a nine-month period and in multiple phases, each focused on inferring the actions of one type of stakeholder.

Our study design and findings advance both notification research and ad fraud research. We first design a multi-phase email-based notification campaign for mitigating dark pooling in the multi-stakeholder ad-tech supply chain (§3). This design provides a template for future multi-stakeholder notification studies. Next, we operationalize this design to identify and notify 2.9K entities (1.7K publishers, 644 ad-networks, and 635 advertisers) involved in and affected by dark pooling vulnerabilities. We analyze their responses to answer the following research questions:

- *RQ1. What are the differences in stakeholder attitudes and responses towards dark pooling vulnerability notifications? (§4)* We conduct a thematic analysis of the stakeholder responses to our notifications. Our approach uncovers three response themes: (1) effort towards resolution; (2) demonstration of concern or awareness; and (3) lack of trust in our data or lack of resources for resolution.
- *RQ2. How does the choice of notification recipient influence the resolution of dark pooling vulnerabilities? (§5.2)* We measure the rates of dark pooling vulnerability resolution when notifications are sent to publishers, ad-networks, and advertisers. We find that sending notifications to ad-networks has the highest influence on dark pooling vulnerability resolution with 81.6% of notified entities remediating dark pools in their network and 76.9% in partner ad-networks. Publishers demonstrate the least effectiveness to notifications, however, with the highest effect size.
- *RQ3. How does the notification sender influence the resolution of dark pooling vulnerabilities? (§5.3)* We compare the efficacy of notifications sent from academics with those from activists with a long history of public advocacy in addressing online advertising vulnerabilities [32]–[34]. We find that notifications sent as activists are generally as effective as those from academics. The only exception is when the notifications are sent to publishers. In this case, activists have a statistically significantly stronger positive effect on the resolution of dark pools.

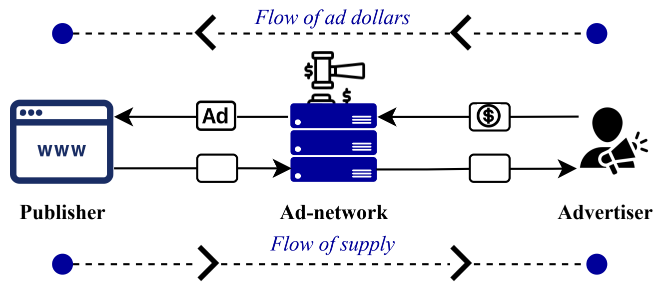

Figure 1: Stakeholders in the ad-tech supply chain

All together, our design, analysis methods, and results provide crucial insights into the applicability of vulnerability notifications in complex, multi-stakeholder environments.

2. Background

In this section, we provide an overview of the online advertising supply chain (§2.1), dark pooling vulnerabilities (§2.2), and vulnerability notification research (§2.3).

2.1. The online advertising supply chain

Stakeholders in online advertising. The online advertising supply chain involves three main types of stakeholders: (1) publishers (i.e., websites), who are the source of the ad inventory; (2) ad-networks (i.e., supply-side platforms and ad-exchanges) that facilitate a real-time bidding marketplace for ad inventory; and (3) advertisers (i.e., brands), who buy ad inventory from publishers to display their ads to users.

How the online advertising supply chain works. Publishers, ad-networks, and advertisers collaborate to create the ad supply chain. When a user visits a publisher's website, the ad inventory associated with that visit is auctioned off at an ad-network (possibly by other ad-network intermediaries called supply-side platforms). Advertisers then make bids on the auctioned ad inventory available at the ad-network (with the help of brokers called demand-side platforms). Finally, the ad-network places the ad from the winning advertiser (e.g., the highest bid) on the publisher's website. The advertiser transfers the payment to the ad-network (possibly through intermediary networks), and deposits a portion of the billed impressions into the publisher's account (possibly through intermediary networks). A simplified version of this process is illustrated in Figure 1.

Control and incentives in the online advertising supply chain. Each ad-tech stakeholder has different levels of control and different incentives.

Publishers. They aim to get the highest bids for their ad inventory by participating in auctions at large ad-networks, enrolling with multiple ad-networks, and showcasing the value of their user base to advertisers. They do not control other parts of the supply chain.

Ad-networks. They earn a fraction of each winning bid at ad inventory auctions. They aim to maximize the number of clients (i.e., publishers and other ad-networks) participating in their auctions and ad inventory sold through their platforms. As facilitators of the ad inventory auction, ad-networks have significant control and visibility into both ends of the supply chain. However, this is diminished when multiple non-collaborative ad-networks participate in a transaction (this is the common case).

Advertisers. Their goal is to ensure their ads reach the right audience. Despite funding the entire supply chain with their advertising dollars, they cannot verify if their ads are shown to the right users and on brand-safe publishers or not.

Challenges associated with the multi-stakeholder supply chain. One consequence of this decentralized multi-stakeholder scenario is that vulnerability resolution is rarely possible without collaboration between multiple, each with their own controls and operating incentives. This interdependence and necessary trust, despite conflicting objectives, between different stakeholders makes the online advertising supply chain a uniquely interesting case-study for assessing the effectiveness of vulnerability notifications.

2.2. Dark pooling vulnerabilities

Seller ID pooling in online advertising. A *seller ID* is assigned to an ad inventory seller's account when they establish a relationship with an ad-network. This seller can be a publisher or another ad-network. Pooling is a strategy used to simplify inventory management for organizationally-related publishers. Sellers owning multiple publishers (e.g., parent organizations with several websites) manage their inventory through a single seller account on an ad-network and receive just one seller ID for the account. This practice allows for efficient operation and inventory management, but current transparency standards make it possible to mask the exact inventory source (publisher) when it belongs to a set of pooled websites sharing the same seller ID. This trade-off is generally accepted due to the assumed similar reputations of publishers owned by the same entity.

How pools become dark? A pool becomes a *dark pool* when the publishers sharing a single seller ID are *organizationally-unrelated and have different reputations* [8]. Dark pooling allows low-quality publishers to disguise their inventory as high-quality, leading advertisers to unintentionally purchase low-quality, brand-unsafe inventory. Malicious publishers or ad-networks can facilitate dark pooling. Simple examples of both types of dark pooling

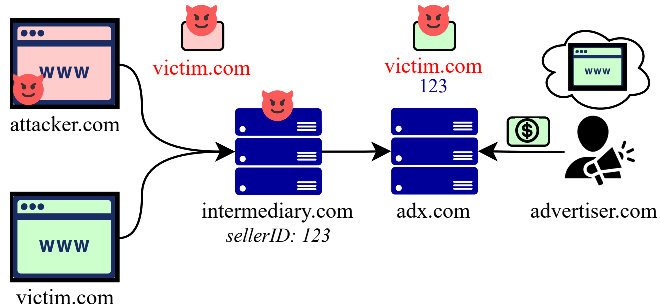

Figure 2: Our threat model representing ad-tech supply chain vulnerability of dark pooling.

vulnerabilities are shown in Figure 2 and explained below. More comprehensive explanations can be found in Vekaria et al. [8] and Papadogiannakis et al. [18]. The remainder of our paper is focused on using notification campaigns to capture the motivations, control, and capabilities of each stakeholder in addressing inventory fraud due to dark pooling.

Dark pooling facilitated by publishers. Recall that publishers aim to join large ad-networks to maximize revenue, which is challenging for low-quality publishers. Dark pooling allows these publishers to misrepresent their existing relationships in order to gain access to large ad-networks. For example, a low-quality publisher (`attacker.com`) manipulates its `ads.txt` file to *intentionally* hide or misrepresent its ad inventory, making it appear as though it belongs to a reputable publisher (`victim.com`). Next, they change the inventory source to `victim.com` in future bid requests. An unwitting brand (`advertiser.com`) might then bid on this inventory, incorrectly believing that it belongs to `victim.com` (even after using `victim.com`'s `ads.txt` file for source verification). Although `attacker.com` may not immediately financially benefit from the inventory sold by this manipulation (payments go to `victim.com`'s account), it is useful for demonstrating a higher value for the ad inventory on its website to other ad-networks. Such manipulation is possible because of: (1) misrepresentations, incompleteness, and inaccuracies within `ads.txt` and `sellers.json` files made available by publishers and ad-networks, respectively; and (2) poor verification procedures by ad-networks which are incentivized to maximize the sale of ad inventory. Vekaria et al. [8] provide a detailed explanation of these manipuations.

Dark pooling facilitated by ad-networks. Intermediary ad-networks (`intermediary.com`) provide 'inventory management' services to smaller publishers unable to manage their own inventory with in-house teams. Dark pooling occurs when these intermediaries share a single seller ID among clients (i.e., publishers) with different reputations. In this case, ad inventory owned by `victim.com` and `attacker.com` auctioned through the `intermediary.com`'s network appears to an advertiser as owned by `intermediary.com` and can be made indistinguishable. Ad-networks are not incentivized to prevent dark pooling as it would reduce the volume of inventory traded.

Industry efforts to mitigate dark pooling. The ad-tech ecosystem has introduced several standards to increase supply chain transparency and mitigate inventory fraud. Notable among these are the ads.txt standard [13], sellers.json standard [14], and the RTB SCO (Supply Chain Object) [16] all introduced by the Interactive Advertising Bureau.

The ads.txt standard. Each publisher participating in real-time bidding is expected to implement and maintain an ads.txt file [13] at the root of their domain. This file lists all the ad-network seller domains (and seller IDs assigned to the publisher by the corresponding ad-network) that are authorized to sell or resell the publisher's inventory.

The sellers.json standard. Ad-networks must maintain a sellers.json file [14] at their domain's root. This JSON file details all publishers and intermediary ad-networks they work with, along with corresponding domains and ad-network-assigned seller IDs.

The Supply Chain Object. SCO is a field in the RTB object that each seller in the supply chain populates using information associated with their inventory source to provide transparency about involved entities. Buyers validate the supply chain in real-time using ads.txt, sellers.json, and SCO, then decide whether to bid on an ad slot.

Unfortunately, prior work has shown that each of these standards has low adoption rates and serious misrepresentation issues which make them unsuitable for preventing inventory fraud [8], [9], [17], [18], [35].

Related academic research. Recent academic research has focused on measuring the prevalence of inventory fraud. Notably, Kline et al. [10] illustrated several supply chain ad attribution exploits which allowed malicious publishers to inflate their ad revenue by making their inventory appear premium. Papadogiannakis et al. [9], [18] showed how problematic websites exploited supply chain complexities to monetize their website using hidden content, pooling, and identity masquerading. Most closely related to this work, Vekaria et al. [8] provided methods to identify dark pooling, measured its prevalence, and showed how it was used to monetize misinformation publishers.

2.3. Vulnerability notification campaigns

Notifications of security and privacy vulnerabilities. Researchers have studied the effectiveness of notifications for warning server operators about unintended abuse of their infrastructure for malicious purposes [27], [36]. They have also examined how well these notifications work for fixing various security vulnerabilities, such as HTTPS misconfigurations [37], issues in version control system (VCS) repositories [30], [38], firewall omissions for IPv6 services [25], DDoS amplification vulnerabilities [25], [39], Heartbleed [40], cross-site scripting (XSS) bugs [24], and others [26], [28], [29], [31], [41]–[43]. More recent, related research has studied the remedial effects of privacy non-compliance notifications [41], [44]–[46]. Despite extensive research on notification campaigns, most studies focus on single-stakeholder scenarios where one entity can resolve a vulnerability. Ours is the first to evaluate notification campaigns in the ad-tech supply chain and any multi-stakeholder scenario.

Notification campaigns in the online advertising supply chain. Although previous research has extensively studied ad-tech supply chain vulnerabilities, it has not examined the effectiveness of large-scale notifications in remedying these vulnerabilities. The work of Vekaria et al. [8] is closest to this study; they conducted a small-scale disclosure of dark pooling vulnerabilities to 55 reputable brands, treating it as a single-stakeholder issue and ignoring the multi-stakeholder aspect of the supply chain. In contrast, we build an effective and large-scale multi-stakeholder vulnerability notification framework for the online advertising supply chain. By focusing on dark pooling, we study the influence and attitudes of each stakeholder (publishers, ad-networks, and advertisers) towards notifications sent from academic researchers and a well-known ad-tech watchdog group, CheckMyAds [34] (i.e., activists). Our automated framework for detecting vulnerabilities and sending notifications is publicly available at <URL blinded for review>, as is the (non-email) data that is the basis of this paper.

Challenges in selecting notification delivery mechanisms. Notification studies often involve the large-scale detection and notification of vulnerabilities [47]–[49]. A common challenge is reliably delivering notifications to the intended recipients. Often, notifications go undelivered due to the lack of publicly known communication channels. Previous research has explored various non-automated notification channels, such as telephone, contact forms on websites, social media accounts, physical mail, and manually identified contact email addresses [30], [31], [38]. These manual approaches achieve high delivery success but require significant manual effort, making them infeasible for large-scale studies like ours, which focuses on the globally distributed multi-stakeholder ad-tech supply chain To address this challenge, researchers have used various automated alternatives for delivering notifications, such as sending them to generic email addresses, or obtaining addresses from hosting providers [27], WHOIS contact information [24], [25], [27], [28], [37], [38], [40], [50], trusted third parties like CERTs or clearing houses [24], [25], [28], [39], and DNS operators [28]. However, these email-based automated approaches often suffer from low delivery success rates due to outdated contact details [24], [27], [28], spam filters [24], [38], or incorrect recipients who do not forward the email to the responsible entity [25]. Additional challenges such as recipients not trusting the senders also emerge [29], [37], [38], [42]. In general, prior research shows a trade-off between scale and deliverability of notifications.

Category	Dataset source (# publishers)	# retained publishers
Misinformation/ Disinformation	[8] (669); [52] (3K); [53] (11); [54] (1.6K); [55] (2.1K)	660
Typosquatting	[50] (10.5K)	14
Phishing	[50] (72.1K)	309
Piracy	[56] (2.7K)	136
Sanctioned	[57] (53)	6

TABLE 1: Categories and counts of problematic publishers in each category used by our study (*cf.* §3.1)

3. Research Methods

In this section, we describe our methods for identifying entities involved in dark pooling §3.1 and the multi-stakeholder vulnerability notification campaign design §3.2.

3.1. Identifying dark pooling vulnerabilities

Curating problematic publishers. Problematic publishers are more than twice as likely to be pooled compared to other publishers [8]. Therefore, we focus on this subset of publishers. Table 1 lists the seven categories of problematic publishers in our dataset. We started by collecting a list of publishers already classified as problematic by prior research. Since identifying these publishers is not our main goal, we used these existing classifications. First, we removed duplicates and checked if the publishers' websites were functional. We discarded 79,938 publishers that were either non-functional or had parked domains. Next, we used an advertising filter list [51] to see if the remaining 12,875 publishers had advertising. As expected, many problematic publishers (like typosquatted publishers) did not have ads. We found at least one advertising request on 1,125 of these publishers. To avoid including legitimate publishers and to confirm the presence of ads, we manually checked the content on these publishers. We kept 684 problematic publishers that had one or more display ads on their homepage. We also included one random subpage from these 684 publishers and from the remaining 441 publishers if the subpage served display ads. Our final dataset contains 1,478 URLs across 1,007 distinct publishers.

Discovering vulnerabilities with static analysis. Here, we use static standards files (i.e., `ads.txt` and `sellers.json`) to discover dark pooling vulnerabilities.

Curating a dataset of standards files. First, we crawl `ads.txt` files from the root of each problematic publishers we are studying, as well as from the Tranco Top-1M websites [58]. We extract the distinct domains of ad-networks listed in these `ads.txt` files (i.e., domains associated with `ads.txt` DIRECT and RESELLER entries). Next, we crawl the corresponding `sellers.json` files from the root of each previously identified seller domain. We extract the distinct ad-network domains listed in these `sellers.json` files (i.e., domains associated with `sellers.json` INTERMEDIARY and BOTH entries). We repeat this process until no new seller domains/entities are discovered. This ensures complete coverage of all supply chain entities involved in the sale of ad inventory on our problematic publishers and the Tranco top websites.

Identifying dark pools from the standards files. We use the above data to identify dark pools by finding all publishers whose `ads.txt` files share a common seller ID with another publisher on some ad-network. We use the `sellers.json` file of the corresponding ad-network to determine the owner of such pooled seller IDs (i.e., the *owner domain*). The ad-network that allows such pooling is referred to as the *pooled domain*. To determine if a pool of publishers sharing a seller ID is a dark pool, we use DuckDuckGo's entity list [59] to map each publisher in the pool to its parent organization. If a pool contains publishers owned by more than one parent organization and includes at least one of the problematic publishers listed in Table 1, then it is classified as dark pool. In total, our static analysis yielded 26.1K dark pools. These pools involved 399 problematic publishers, 1.7K unique victim publishers, and 962 unique ad-networks.

Discovering vulnerabilities with dynamic analysis. As highlighted in prior work [8], static analysis alone cannot prove that dark pooling is actually occurring. This is because each publisher is responsible only for the content of their own `ads.txt` files and have no control over the misrepresentations in other publishers' `ads.txt` files. Therefore, we also perform dynamic analysis to gather evidence that a problematic publisher is actually monetizing its ad inventory using another publisher's seller ID.

Identifying entities associated with dark pools from live page loads. We follow the methodology developed by Vekaria et al. [8]. Following the crawling configuration and disclosures recommendations of Ahmad et al. [60], we used a stateless web crawler driven by Selenium (v4.1.0) and the Chrome browser (v117.0) with bot mitigation strategies and Xvfb from a non-cloud vantage point to crawl problematic publishers and capture HTTP archive (HAR) files. During each dynamic crawl, we load the problematic publisher, we wait 30 seconds for all resources, including ads, to finish loading. We click on the DOM elements associated with each ad URL and wait for the advertiser's website to be loaded. We log the associated URL, the chain of redirects, requests, responses, and payloads using the HAR file format. Then, from our HAR files, we extract any strings which have a 'key:value' or 'key=value' format. We examine if any of the seller IDs associated with our static dark pools appear in these extracted pairs. If they do, we log the crawled website (publisher), the pooled seller ID, the ad-network that issued the pooled seller ID, the domain to which the pooled seller ID was issued to (owner domain), and the advertiser whose creative was served. In a normal transaction, we expect that the owner domain matches the crawled publisher website, or that they are at least organizationally-related. However, in our current scenario examining dark pools containing problematic publishers, the owner domains are (victim) publishers who are not associated with the problematic publishers. In total, our dynamic analysis yielded 1.3K dark pools which included 200 unique ad-networks, 347 unique owner domains, and 889 unique pooled seller IDs. The problematic publishers in these dark pools were observed with ads from 635 unique advertisers.

3.2. Designing multi-stakeholder notifications

Identifying notification recipients. During our study, we sent notifications to the three types of stakeholders (*cf.* §2.1) in three separate rounds. This allowed us to measure each stakeholder group's influence in remedying the dark pooling vulnerability accurately.

Round 1: Notifying victim publishers. We notified all popular (i.e., Tranco top-10K) publishers involved in dark pools with one of our problematic publishers, identified through our static analysis. We identified 1.7K such publishers.

Round 2: Notifying ad-networks. We notified all of the ad-networks that facilitated *more than one* dark pool with one of our problematic publishers, identified through our static analysis. We identified 644 such ad-networks as recipients.

Round 3: Notifying advertisers. We notified all the advertisers whose creatives were observed on problematic publishers due to dark pooling. We identified 635 unique advertisers.

Ordering of stakeholders. This is a crucial design choice that multi-stakeholder notifications should evaluate as it can impact how different stakeholders respond and remediate vulnerabilities. In our case, the ordering of notifications was decided based on our intuition about which stakeholders would be most influential at remedying vulnerabilities. We hypothesize that notifications to victim publishers are least influential because they are not monetarily impacted (at least directly) by the vulnerability and also do not have the ability to influence pool memberships directly. Ad-networks, on the other hand, have the ability to re-assign pool memberships when they are the issuers of the pooled seller ID. However, doing so has the potential to lower the revenue generated by their pooled inventory. In contrast, we hypothesize that notifications to advertisers will be most influential since they are the most affected stakeholder, from monetary and reputation perspectives. Additionally, their ability to control the flow of revenue to other stakeholders also makes them more capable of influencing their actions. Therefore, our ordering (notifying publishers, then ad-networks, and then advertisers) is expected to leave enough unresolved dark pools to allow for valid statistical analysis in each round.

Establishing notification channels with recipients. We used emails to communicate with notification recipients, similar to the most prior works. We obtained email addresses from four sources outlined below and attached a tracking pixel to our notifications to see if recipients opened them.

Source 1: Contact pages. We searched the recipient's homepage DOM for links containing the word "contact" to find the URL of the contact page. We then scraped these pages to retrieve email addresses using the regex: `[\w\.-]+@[\w\.-]+\.\w+`. This method works only with English websites.

Source 2: `ads.txt` files. We extracted publisher email addresses from their `ads.txt` files, whenever available. A typical `ads.txt` email address is present in the following format: "`CONTACT=adstxt@bbc.com`". Per the `ads.txt` standard, this email address is meant to represent the point of contact to report issues regarding `ads.txt` file of the associated publisher domain.

Source 3: `sellers.json` files. We extracted ad-network email addresses from their `sellers.json` files. These addresses are extracted from the `contact_email` key in the `sellers.json` file. Per the `sellers.json` standard, this email address may be used to contact the Advertising System for questions or inquiries about the associated `sellers.json` file.

Source 4: Common email prefixes. As a final resort, we also consider email prefixes commonly seen in contact emails by different companies. These included `info@`, `support@`, `help@`, `webmaster@`, and `contact@`. If the other methods did not provide an email address, we tested the availability of these common addresses. To ensure deliverability of our notifications, we sent test emails from an alternate account and monitored for bounce messages, preserving the sender reputation of the main email account used for the notifications.

Varying sources of notifications. To measure the influence of the background and status of notification sources on the vulnerability resolution we randomly divide the notification recipients in each round into three equal-sized groups: two treatment groups and one control group. Entities were assigned to these groups at the start of each notification round.

Treatment 1: Academics as notification sources ($\mathcal{T}_1$). We used a dedicated university email address for notifications to recipients in this group. These notifications had university branding and mentioned our university affiliations.

Treatment 2: Activists as notification sources ($\mathcal{T}_2$). We collaborated with the Check My Ads (CMA) institute [34] (previously known as "Sleeping Giants" [33], [61]), a well-known activist organization which names-and-shames ad-tech entities that aid the monetization of problematic content. Unfortunately, due to organizational limitations (*cf.* §6.2), we couldn't use CMA's servers for sending these emails and used our university servers instead. However, recipients in this group received notifications which had CMA branding and explicitly mentioned CMA's involvement.

Control group ($\mathcal{C}$). The control group received no notifications from us. They were used as a baseline from which the effects of $\mathcal{T}_1$ and $\mathcal{T}_2$ notifications could be measured. Entities in this group were informed of their dark pooling vulnerabilities at the end of our 9-month long study.

Curating notification content for stakeholders. All notification emails contained brief introductions to the researchers along with a link to our project webpage.

The project webpage. The webpage contained a description of our research project's goals and dark pool identification methodology. This page also contained FAQ and Contact sections to help recipients better understand their notifications or reach us. In our descriptions and notifications, we consciously avoid alarmist or accusatory language. For example, we use the term 'ad safety research' in lieu of 'ad fraud research' and consistently describe the identified vulnerabilities as 'potential vulnerabilities' and problematic publishers as 'potentially unsafe websites'. This is done to develop a positive relationship with the entities and show intent to aid vulnerability resolution.

Subject lines of notification emails. Notification emails to advertisers had the subject line: *Brand safety violation for your domain* `<advertiser.com>`. Other notification emails to ad-networks and publishers had the subject line: *Potential ad inventory vulnerability for your domain* `<domain.com>`.

Body of notification emails. In addition to an introductory preamble described earlier, the body of notification emails contained summaries of the vulnerabilities identified by our research. We crafted unique summaries for each stakeholder.

- *Victim publishers.* We report vulnerabilities (i.e., from static and dynamic analysis) using the following text summaries: (1) For vulnerabilities detected via dynamic analysis: "During network traffic analysis of problematic publishers, we observed that `<Number>` sellerID(s) in your `ads.txt` are being used by `<Number>` potentially problematic publisher(s) to monetize their ad inventory."; and (2) For vulnerabilties detected via static analysis: "We observed that `<Number>` sellerID(s) in your `ads.txt` are being used in `ads.txt` of at least `<Number>` other potentially problematic publishers."
- *Ad-networks.* We report two types of vulnerabilities from each of our analysis approaches using the following text summaries: (1) For vulnerabilities detected by static analysis of `ads.txt` files: "`<Number>` seller IDs issued by you are being pooled by `<Number>` potentially problematic publishers."; (2) For vulnerabilities detected by static analysis of `sellers.json` files: "`<Number>` seller IDs owned by you and issued by another ad-network are being pooled by `<Number>` potentially problematic publishers."; (3) For `ads.txt` vulnerabilities confirmed by dynamic analysis: "We confirmed that `<Number>` seller IDs issued by you are being pooled by `<Number>` potentially problematic publishers."; and (4) For `sellers.json` vulnerabilities confirmed by dynamic analysis: "We confirmed that `<Number>` seller IDs owned by you and issued by another ad-network are being pooled by `<Number>` potentially problematic publishers".
- *Advertisers.* Because we do not expect advertisers to be particularly technically adept, we frame our notification around the presence of their ad creatives on potentially problematic content as follows: "An ad creative associated with your brand was observed on `<Number>` problematic publishers. This association could negatively impact your reputation and future business."

Reports attached to notification emails. To provide concrete evidence to support the reported vulnerabilities, we generated an automated PDF report, with appropriate branding based on the notification source. This report contained: (1) up to 25 instances of vulnerabilities which involve the specific entity; (2) an explanation of the root causes and implications of each vulnerability; and (3) possible remediation options. In addition, notifications to advertisers also included attachments of screenshots which showed the advertiser's ad creative on a problematic publisher and the HAR file associated with the page load.

Timeline of notifications. Figure 3 depicts the timeline associated with our notification campaign. Prior to each round of notifications we conduct static and dynamic analysis to identify dark pooling vulnerabilities which involve our dataset of problematic publishers (*cf.* §3.1). Then, we generate and send our vulnerability notifications and reports for each entity associated with that round. If we do not hear back, we send a reminder email approximately 1-2 weeks after the initial email. We then wait a month before once more conducting our static and dynamic analysis. We use the data from this analysis to assess the influence of notifications sent during the current round.

4. Recipient Engagement with Notifications

Our study included a total of 2.9K unique entities who were involved in or impacted by dark pooling in the online advertising supply chain. These included 1.7K victim publishers, 644 ad-networks, and 635 advertisers. In this section, we report the rates of engagement (§4.1) and the nature of engagement (§4.2) with our notifications by these entities.

4.1. Rate of engagement with notifications

Notification delivery rates. Of the 2.9K entities involved in our study, we only sent notifications to two-thirds (*cf.* §3.2) and used the remaining one-third as a control group against which the effect of our notifications could be determined. Of these 1.9K notifications (across both treatment groups $\mathcal{T}_1$ and $\mathcal{T}_2$), 79.5% were successfully delivered and opened by their recipients. This rate of delivery exceeds the rates reported in prior notification research [24], [27], [28], [38]. We hypothesize that this is because of our ability to leverage email addresses from `ads.txt` and `sellers.json` files for contacting publishers and ad-networks, respectively. The remaining notifications (417 notifications or 20.5%) failed to be delivered for a variety of reasons including emails rejected by spam filters (40.2% of failures) and invalid email address (21.5% of failures).

Notification response rates. Of the 1.5K recipients who read our notifications, we received an email response from 215 (14%). Of these, 147 emails were generic responses that appeared to be template responses. The remaining 68

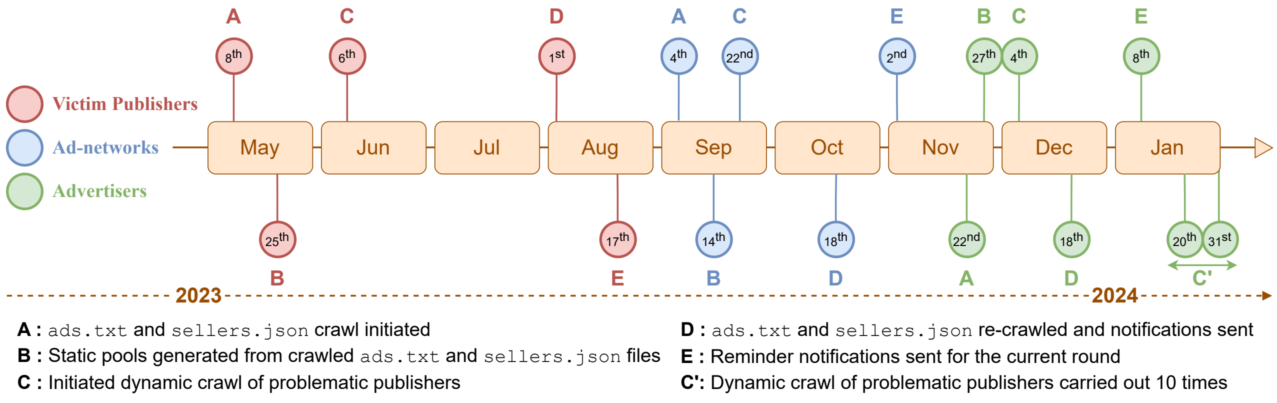

Figure 3: An overview of the timeline of the the notification campaign.

emails were engaging directly with the content of our notifications and were qualitatively analyzed (*cf.* §4.2). Of these, 40 were from victim publishers (3.5% response rate), 18 were from ad-networks (4.2% response rate), and 10 were from advertisers (2.9% response rate). This is in line with the response rates observed in prior research [30], [31], [38], [44]–[46] focused on single-stakeholder notifications. It should be noted that the absence of an email response does not suggest that the notifications did not influence vulnerability resolution. We measure the exact influence on vulnerability resolution in §5.

4.2. Nature of engagement with notifications

Methodology for thematic analysis. To systematically explore different themes emerging in responses to our notifications, we adopted the state-of-the-art thematic analysis methodology [44], [62] to identify, analyze, and report patterns in the responses. This analysis can uncover common attitudes towards and challenges faced in the ad-tech vulnerability resolution. One author familiarized themselves with the email responses by reading them multiple times. Next, a codebook was developed by the same author by assigning codes to each sentence in the response emails. This codebook was iteratively refined, in consultation with the other authors, to consolidate the final set of codes in our codebook. Next, the authors use this codebook to independently code all the emails. Following Clarke and Braun's [63] understanding of thematic analysis, we also did not calculate inter-rater reliability (similar to Stover et. al [44], which used the same thematic analysis methodology). Instead, the authors convened to deliberate any ambiguities and reach a consensus on the final coding in order to ensure a high quality of analysis. Finally, the email responses were grouped into three high level themes: (1) effort towards resolution, (2) demonstration of concern or awareness, and (3) lack of trust or resources. The codebook, identified themes, categories, and sub-categories is presented in Table 2. Next, we use the developed codebook categories to study responses by themes, recipient type, and sender reputation (*Cf.* Figure 5 in the appendix).

Response theme 1: Effort towards resolution. We found that victim publishers and ad-networks often requested additional actionable information or clarifications to aid the resolution of our reported issues. This is not commonly seen in responses from advertisers, however. We hypothesize that this is because advertisers are less likely to maintain in-house tech-teams and instead rely on ad agencies to manage their ad campaigns for them. This hypothesis is supported by the high number of *forwarded to the right department* category responses observed from advertisers. This suggests that most of the generic contact emails available on a advertiser's website may not be particularly useful for performing advertiser notifications related to ad-fraud. In contrast, victim publishers yielded a mix of responses under this category – smaller publishers did not have separate teams for advertising, however, larger publishers managed advertising under a separate team to which our notifications were forwarded. We found that many of the responsive victim publishers and ad-networks were motivated to *collaboratively resolve the issues* and scheduled either a video meeting or a phone call to understand and resolve the reported vulnerability. Victim publishers were most likely to have responded following a successful resolution of the reported vulnerability. For example, one victim publisher responded – "*We've cleaned up our `ads.txt` to only active providers. Can you check it again?*" – suggesting that they do not regularly update their `ads.txt` files to maintain them up-to-date. Untimely updates can aid problematic publishers to monetize through victim publisher's sellerIDs.

Response theme 2: Demonstration of concern or awareness. Responses to our notifications were largely positive, with many including a note of thanks for our report and showing concern and motivation to resolve the vulnerability. Even those that started as negative eventually turned positive as engagement continued. For example, one entity who initially responded "*I find your email frustratingly alarmist and devoid of actionable information*" eventually appreciated our notifications and research after several back-and-forth emails in which we provided clarifications and help towards vulnerability resolution. Some publisher recipients

TABLE 2: Code book with themes, categories, and subcategories that resulted from the thematic analysis of notification responses.

Category	Subcategories	Frequency
Theme 1: Effort towards resolution		
Actionable details requested	asked for additional details (13); seeking clarification on conveyed information (11); asked technical questions (4); asked methodology to contact problematic entities (2); data collection time period details requested (2); requested the full report (2); tried to identify root cause of the issue (2); verifying if vulnerability is due to reseller relationships (2); action items requested (1); actionable information acknowledged (1); ad screenshot requested to see evidence of issue (1); confirming the external inventory scanning tool used by us (1); discussed possible solution to implement (1); Seeking details on how to fix the issue (1); technical details shared (1)	28
Forwarded to the concerned team	shared with the relevant department (7); will share with the relevant department (7); security reporting procedure explained (5); asked to contact other department (3); escalated the issue (2)	22
Collaborative resolution performed	scheduled a meeting (10); suggested collaborative issue resolution (3); engaged in phone call (1); suggested collaborative business promotion (1)	14
Fixed reported issues	made fixes (7); asked to verify current status of issues post resolution (2); investigated the issues (2); removed off the vulnerable entries present in the report (2); actively fixing the issue (1); ads.txt added but never used (1); sellers.json had stale entries (1); will not engage in further correspondence on security issues (1)	11
Contacted responsible entities for fix	will reach out to responsible entities (6); reached out to responsible entities (3)	9
Justifying the issue	defending few reseller relations (1); justifying low inventory fraud rate due to the usage of brand-safety tools (1); questioning vulnerabilities as benign due to direct relations (1); stating to work via mostly direct-business relations (1)	4
Theme 2: Demonstration of concern or awareness.		
Acknowledged the notification	acknowledged the notification positively (47); grateful for sharing the information (2)	47
Motivated to fix	will investigate on the issue (13); will resolve the issue (8); willing to help fix the issue (3); will remove ads.txt (1); will remove vulnerable entries from sellers.json (1)	21
Concerned about the notification	concerned about the issue (5); confused in interpreting intended versus actual recipient (3); activists are anti-Fox where Fox is our biggest customer (1); cared about phrasing/wording of the notification (1); concerned about the already incurred effect on reputation (1); concerned about the potential loss of ad revenue already incurred (1); contacted consultant about the notification (1); curious about recipient selection for notification (1); demonstrated seriousness about the notification (1); expressed surprise from the details in the notification (1); lawyer reached out (1); misinterpreted reaching out to hosting provider (1); notification perceived as frustratingly alarmist in nature (1); were afraid of the effect of the notified issue on business revenue (1); worried about vulnerability's impact on web traffic (1)	15
Research initiative appreciated	research perceived as interesting (3); received appreciation for research (2); admired the research (1); considered initiative to be similar to another initiative (1); considered work being done as very important (1); conveyed appreciation for initiative (1); expressed willingness to connect in the future (1); the initiative perceived as interesting (1); showed support for initiative (1)	9
Awareness about the vulnerability	were already aware of the issue (2); advocated awareness around the issue in the industry (1); were aware of our research via publisher notification (1); were unaware of the issue (1)	4
Notification unhelpful or uninterested	considered notification as not helpful (1); demonstrated unseriousness about the notification (1); no documentation (1); not interested in the notification (1); perceived no actionable information (1)	4
Theme 3: Lack of trust or resources.		
Doubting correctness of the report	asked for the definition of problematic (7); felt that the report had some inaccuracies (2); doubted the association of reputable big ad-networks with the vulnerability (1); doubted the data viability (1); felt that the report didn't make sense (1); not sure if the report was accurate (1); notified about 0 issues (1); verified no threats to be present (1)	13
Misinterpreted as phishing	authentication of the sender (6); misinterpreted as a phishing attempt (2); company policy prevented opening external documents (1); considered notifications as spam (1)	9
Limited resources to fully resolve	expressed to be a small publisher (2); considered time-consuming to reach out to publishers (1); expressed a lack of resources to fix the issue (1); unsure how to handle issues with a large number of domains (1)	4
Complete resolution beyond control	expressed no say in the removal of their entry from other ads.txt (1); expressed zero control over reseller accounts (1); removal from other ads.txt not in our control (1)	3

were eager to act but didn't know how to go about resolving dark pools. For example, "*We truly want to prevent dark pooling from happening. What do you suggest that we should do? ...can we reach out to [ad-networks] and ask them to monitor and provide logs for the usage of vulnerable sellerIDs that you provided?*" Many entities showed concern regarding the indirect effects of the reported vulnerabilities on their reputation and revenue. For example, one entity responded: "*is there some way of estimating how much potential harm may have been caused to our website — as far as reputation and ad revenue go — from the kinds of activity that you identified in your research?*", later adding "*if these ad inventory vulnerabilities have played a part in [our] revenue decline, I'd really like to know to what extent they have — and what we can do to get back any potential loss in revenue*". Other responses showed awareness about the types of vulnerabilities reported and appreciation for our research efforts. For example, one entity responded – "*This matter is near and dear to me, and I've spoken about it publicly at [ad-tech conference] as well as on the [podcast]*" ... "*Beyond all this, I think the work you're doing is necessary for our industry.*"

Response theme 3: Lack of trust or resources. Several entities highlighted their inability or unwillingness to resolve the reported vulnerabilities for a variety of reasons ranging from doubting the correctness of the report to a lack of technical resources to properly understand and resolve the vulnerabilities. In one interesting case, an ad-network claimed our report (which contained evidence that a misinformation publisher was pooling a seller ID issued by them) was inaccurate — "*My tech team verified that all the references on your list are legitimate publishers owned by one of the corporate entities on our small inclusion list*"; yet, within hours, this same ad-network updated their `sellers.json` file with a comment "*We no longer work with [misinformation publisher] or any of its associated properties.*" Several entities also suspected that our notifications were part of a phishing campaign and accordingly delayed resolution actions. These entities often sought proof of our identities, with several even reaching out to our university's media relations team for clarification. "*... a lawyer who received an email from your address yesterday is concerned about the issue that this email may have been a phishing attempt.*". Fortunately, these suspicions were eventually resolved favorably. Finally, many publishers reported their inability to resolve the reported vulnerabilities due to the lack of technical resources — for example, one publisher reported "*I've made some immediate fixes — basically, just cleaning up our `ads.txt` file, removing the lines in question but also deleting a lot of probably unnecessary other lines as well. Beyond that, I'm not sure how to contact all the various other players — the ad-networks, the problematic websites. We're a very a small publisher...*". This lack of technical know-how was also found to be the cause of several reported vulnerabilities, as one publisher reported – "*I had no idea that there was any issue with our `ads.txt` file. I've always just included whatever lines that [AdX] tell us to add.*"

Overall, we observe that notifications sent as academic researchers received less responses as compared to activists for victim publishers. However, ad-networks show more positive responses towards academic researchers than activists. This is a very interesting insight. CheckMyAds (i.e., *activist*) often publicly calls out ad-networks on social media platforms shaming them for monetizing problematic outlets. This seems to have lost the trust of ad-networks. In line with this finding, one of the ad-networks mentioned – "*... admired the research, but your site shows a lot of anti-Fox News posts, and they're one of our biggest publishers*".

5. Notification Impact on Dark Pooling

Our qualitative analysis on responses to notifications does not provide a complete picture on their impact because recipients may initiate remedial actions without responding to the notification emails. In this section, we examine two metrics for assessing the influence of notifications (§5.1). We then use these to measure how the notification source (§5.3) and recipient (§5.2) influence remedial responses.

5.1. Assessing the impact of notifications

Propensity matched difference-in-differences (PM-DiD). Our goal is to uncover the overall impact of notifications on specific measures of dark pooling relevant to each stakeholder. We use *propensity-matched difference-in-differences*, a common statistical approach for identifying the causal effect size of an intervention when a randomized controlled trial is not possible [64]–[66]. We apply PM-DiD in 3 steps.

Step 1: Matching entities in treatment and control groups. First, we create a control group that is statistically similar to the treatment group based on specific dark pooling measures. Our treatment group may be $\mathcal{T}_1$, $\mathcal{T}_2$, or $\mathcal{T}_1 \bigcup \mathcal{T}_2$ and our control group is some subset of $\mathcal{C}$ (*cf.* §3.2). For each entity in our treatment group, we find the entity in the control group candidates which is the most similar for the given measures (i.e., its pre-notification nearest neighbor) and include this candidate in our control group.

Step 2: Computing pre- and post-intervention measures. Next, we identify the pre- and post-intervention measures for each entity in the treatment group (t) and their matched control counterpart (c). We record pre-intervention measures (t_{pre} and c_{pre}) from crawls that occur 1-2 weeks before sending notifications to the treatment entity. We record post-intervention measures (t_{post} and c_{post}) from crawls that occur 4-5 weeks after sending notifications. An illustration of effective remediations is provided in Figure 4.

Step 3: Computing effect sizes and statistical significance. We compute the effect size as: $\Delta_{(t,c)} = (t_{post} - c_{post}) - (t_{pre} - c_{pre})$. A negative value denotes that the corresponding measure is lower post-treatment. We repeat this to compute Δ for each matched (t, c) pair. We then report: (1) $N_{\text{rem.}}$: the number of (t, c) pairs that showed a remedial action (i.e., $\Delta_{(t,c)} < 0$); (2) $\mu_{\text{ov.}}$ the mean effect size across

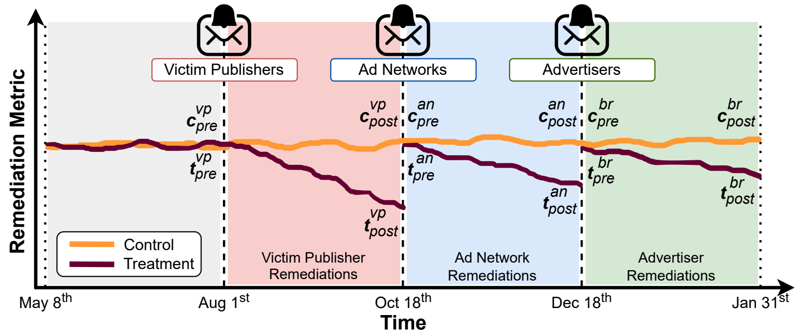

Figure 4: An illustration of the measured remediation metrics before and after notifications in different rounds to different stakeholders. The difference-in-differences is computed from these metrics as $\Delta_{(t,c)} = (t_{post} - c_{post}) - (t_{pre} - c_{pre})$ for each ad-tech entity.

all (t, c) pairs; and (3) $\mu_{\text{rem.}}$: the mean effect size across all (t, c) pairs that showed a remedial action.

Measures of dark pooling for each stakeholder. We track the following dark pooling metrics to measure the impact of our notifications on each stakeholder.

Victim publishers. We focus on one key metric: the number of problematic publishers which pool and use the seller ID of the victim publishers (we refer to this count as $probdomains_{vp}$ for a publisher vp). We expect $probdomains_{vp}$ to reduce if vp engages with their ad-networks to either get: (1) an unpooled seller ID, (2) assigned a different pool than the problematic publishers, or (3) remove problematic publishers from their pool.

Ad-networks. We use two metrics for ad-networks: (1) the number of seller IDs they issue that are used for dark pools (we refer to this as $pools_{ad}$ for the ad-network adx); and (2) the number of seller IDs issued by other ad-networks to adx that facilitate dark pooling (we refer to this as $partnerpools_{ad}$ for adx). We expect $pools_{ad}$ to decrease if adx corrects its own pool assignments to prevent pooling of problematic and popular domains. We expect $partnerpools_{ad}$ to decrease if adx engages with other ad-networks where it is listed to correct their facilitation of dark pools.

Advertisers. Our notifications to advertisers only informs them about the ad-network responsible for displaying their ads on problematic publishers and the associated seller ID. Therefore, we expect a reduction in $pools_{ad}$ for the responsible adx if the advertisers request to remove such $pools_{ad}$. The fact that advertisers monetize the ad-tech supply chain would motivate ad-networks to act.

5.2. Effect of notification recipient

Table 3 shows the impact of notifications on dark pooling metrics for each stakeholder. The data reveals several interesting findings. Notably, all stakeholders are generally responsive to our notifications with between 54-82% of them showing a remedial action (i.e., $\Delta_{(t,c)} < 0$).

Ad-networks are most responsive; publishers are least responsive. At the less responsive end, 54% of notified publishers took successful remedial action, reducing their participation in dark pools more than their control counterparts. In contrast, 81.6% of notified ad-networks took successful remedial action, reducing the number of seller IDs used for dark pooling at a higher rate than their control counterparts. Rather surprisingly, despite controlling the revenue of the advertising supply chain, only 72% of advertisers showed some mitigation in dark pools. This finding might be explained by the fact that, among all the stakeholders, ad-networks can mitigate dark pools most easily because they control their own assignment of seller IDs. On the other hand, publishers and advertisers need to engage with their ad-networks. Our qualitative analysis supports this, showing that many publishers were unsure how to resolve their participation in dark pools. Moreover, this analysis shows that ad-networks remediate dark pools with a higher probability when advertisers reach out to them as compared to when publishers do so – likely because advertisers are actually the source of funding in the ad-tech supply chain.

Recipient (Metric)	$N_{\text{rem.}}$	$\mu_{\text{ov.}}$	$\mu_{\text{rem.}}$
Publishers ($probdomains_{vp}$)	54.0%	2.9	-30.2
Ad-networks ($pools_{ad}$)	81.6%	-0.7	-1.5
Ad-networks ($partnerpools_{ad}$)	76.9%	3.2	-1.4
Advertisers ($pools_{ad}$)	72.6%	0.7	-0.7

TABLE 3: Effect of notification recipient on dark pooling.

Ad-networks are able to successfully engage with their counterparts to perform remedial actions. Our analysis also shows that ad-networks successfully engage with their counterparts to remediate dark pools that they belong to in 77% of cases, as evident by the $partnerpools_{ad}$ measures.

The effect size associated with successful publisher remediation is the highest. Finally, the effect size associated with successful publisher remediation is significantly higher than other measures ($probdomains_{vp}$ $\mu_{\text{rem.}}$ = -30.2). This is because victim publishers are often in very large pools which have many problematic publishers. Therefore, a single remediation action, like assigning the publisher a new seller ID, drastically impacts $\mu_{\text{rem.}}$.

Source	Recipient (Metric)	$N_{\text{rem.}}$	$\mu_{\text{ov.}}$	$\mu_{\text{rem.}}$
Academic	Publishers (*probdomains*$_{vp}$) *	52.3%	5.8	-27.6
	Ad-networks (*pools*$_{ad}$)	81.2%	0.8	-1.7
	Ad-networks (*partnerpools*$_{ad}$)	75.3%	5.6	-0.7
	Advertisers (*pools*$_{ad}$)	72.6%	1.1	-0.9
Activist	Publishers (*probdomains*$_{vp}$) *	55.6%	-0.1	-32.5
	Ad-networks (*pools*$_{ad}$)	82.0%	-0.6	-1.3
	Ad-networks (*partnerpools*$_{ad}$)	78.4%	0.9	-2.0
	Advertisers (*pools*$_{ad}$)	72.6%	0.4	-0.6

TABLE 4: Effect of notification source on measures of dark pooling for each stakeholder. * denotes a statistically significant (t-test; p <.05) difference in the overall effect based on notification source.

5.3. Effect of notification source

Table 4 shows the impact of notifications sent by academics and activists on the stakeholders' remedial actions. The data indicates that, with one exception, there is no significant difference in remediation rates between notifications sent as academics and those sent as activists.

Publisher responses are influenced by the notification source. We compared the distributions of $\Delta_{(c,t)}$ for academic notifications ($t \in \mathcal{T}_1$) and activist notifications ($t \in \mathcal{T}_2$) using a t-test to see if stakeholder responses varied significantly by notification sources. We found that only publishers showed a statistically significant difference in their responses. Publishers were more likely to perform remedial actions when they received notifications from activists rather than from academics. This difference is evident in both the fraction of publishers that performed a remedial action and the mean effect size of the remedial action. This is likely due to CMA's long-standing reputation of publicly name-and-shame ad-tech entities by calling them out on social media for monetizing problematic content online. This is aligned with our findings in the qualitative analysis (*cf.* 4.2).

6. Discussion and Conclusion

In this section, we consider the validity of our study design (§6.1), the limitations of our research (§6.2), ethical considerations (§6.3), and implications for multi-stakeholder notification studies (§6.4)

6.1. Validity of study design

Internal and external validity considerations. Internal validity measures how well a study is conducted and how accurately its results reflect the studied group, while external validity assesses the generalizability of the findings. We evaluate different internal and external validity threats applicable to our study and explain how we handled them to minimize any validity issues. We follow recommendations from prior works [67], [68] to ensure the validity of our study and results.

Threats from lack of representativeness. We ensured representativeness by notifying all entities found to participate in dark pooling, without imposing selection criteria for ad-networks and advertisers. However, problematic publishers often impersonate popular publishers. So, we selected our sample from the Tranco top-10K publishers whose advertising identifiers were used by problematic publishers in their `ads.txt` files. We randomly assigned the selected entities into different treatment and control groups to avoid selection bias. We applied the same treatment steps to different entities, though the specific vulnerabilities disclosed and remediation steps suggested varied based on their role in the ad-tech supply chain. We did not introduce any other experimenter bias.

Threats from subject attrition. We did not measure the long-term effects of notifications on entities, so attrition concerns are not relevant. Additionally, ad-tech entities do not change roles over time (e.g., a publisher does not become an ad-network). We ensured blinding by not informing participants about the applied treatment or intervention. We did not perform any experimental manipulation, such as entitiy-specific priming or incentives.

Threats from situational factors. Our notified entities are spread across the globe. We did not account for situational factors like the time and date of notification or location, which could affect the external validity of our results. We acknowledge this limitation.

Threats from lack of trust and realism. To improve external validity, we aimed for psychological realism [69] by communicating through our email text and website content that we were working in the entity's favor, aiming to reduce their participation in a problematic activity. This approach developed their trust in us, increasing confidence in our notifications. Our notifications were also based on verifiable real data which reflected their true participation in dark pools, further bolstering realism and building trust.

6.2. Limitations

Multi-stakeholder interdependence. The online advertising multi-stakeholder supply chain is fundamentally interdependent with mixed incentives for each participant. Publishers and advertisers cannot directly fix their participation in dark pooling without cooperation from ad-networks. Ad-networks can address their own facilitation of dark pools but cannot control the behavior of other ad-networks using their platform. Using a single round notification (notifying all stakeholders simultaneously) would make it impossible to identify which entity resolved the vulnerability. To solve this, we used a multi-round notification design, notifying one stakeholder in each round. This approach allows us to identify more confidently which stakeholder resolved the vulnerability. However, there is still a risk of contamination when a stakeholder responds much later, after the next round has begun. We minimized such risks by leaving 4-5 weeks between each round of notifications, giving each stakeholder ample time to respond and remediate. Based on the email responses, we observed that nearly all arrived within two weeks of the initial notification. Additionally, publishers may reach out to ad-networks to remediate the vulnerability, before we notify ad-networks in the second phase, alerting them. However, publishers are incentivized to work with more ad-networks and vice versa to maximize their respective revenue. Hence, we acknowledge that complete isolation is not possible. However, since we detect vulnerabilities before each phase, ad-networks were notified of different or unresolved entities than the ones in notifications to publishers, guaranteeing confidence in the results we observe. We believe these approaches effectively addressed the challenge of interdependent multi-stakeholder notification research.

Source of activist notifications. We sent our activist notifications in collaboration with the CheckMyAds Institute, a well-known organization in the ad-tech community. Due to operational constraints, we could only use their branding on our emails, reports, and the website. We could not use their email servers to send notifications due to risks to their server reputation and potential interference with their operations. This might have influenced how recipients perceived the email. To minimize this impact, we clearly stated CheckMyAds' involvement in the opening sentence of the notification and used their branding prominently in the headers and footers of our emails, reports, and website.

6.3. Ethical considerations

IRB review. Our institutional review board (IRB) reviewed this notification study and deemed it as not involving human subjects. Despite this, we designed and conducted our measurements and notifications following the principle of beneficence outlined in the Menlo Report [70] and Belmont Report [71]. We aimed to maximize benefits and minimize potential harms.

Infrastructure costs and risks. We measured ad-tech supply vulnerabilities through crawls. To avoid stressing web servers, we did not conduct dynamic crawls of problematic publishers concurrently. We spaced out our additional crawls for `ads.txt` and `sellers.json` files between 12 days to one month apart. Our crawlers did not follow the robots.txt directives on problematic publishers, but our methodology aligns with ethical and legal considerations for such audits [72]. We sent notifications from a dedicated email server, set up with our university's IT staff, to protect the reputation of the university's mail servers.

Privacy risks. We did not collect or record any personal information in this research. Although we had phone calls and virtual meetings with several organizations to help them remediate vulnerabilities, we did not record or share any conversations or emails with anyone other than the authors.

Advertising costs. To understand which brands advertise on problematic publishers and which ad-networks are responsible, we clicked on the ads shown during page loads. The costs associated with our 28,376 ad clicks were relatively minor, as per-ad CPMs are low, particularly for browsers without profiles [73], [74]. These costs are justifiable given the benefits of understanding and remedying supply-chain vulnerabilities in the ad-tech ecosystem.

Privacy issues in online advertising. Online advertising supports many web services. While many argue that the ad-tech ecosystem engages in questionable privacy practices (and we agree), we believe that approaches for improving its safety/security must be explored as it benefits users and stakeholders alike.

6.4. Concluding remarks

Implications for online advertising. Our research illuminates how the online advertising supply chain functions and how different stakeholders interact. Our qualitative analysis shows that notifications can raise awareness about vulnerabilities in the supply chain, leading to increased transparency, trust, and the termination of relationships with problematic actors. While notifications can effectively address vulnerabilities like dark pools in the online advertising ecosystem, there are important nuances. The motivations and capabilities of notification recipients play a crucial role. We found that publishers have the lowest dark pool remedial rates among stakeholders. In contrast, ad-networks, with their capability and resources, and advertisers, with their monetary incentives, are significantly more effective at resolving dark pools. Additionally, we found that the source of the notification, whether from activists or academics, does not affect dark pool resolution, except for publishers. Future work can investigate other notification channels (e.g., public naming and shaming [75]) and external stakeholders (e.g., direct consumer notifications [76]).

Implications for other supply chains. Our results highlight the need to consider the complexities of multiple stakeholders in other ecosystems, such as the software supply chain, which includes operators, administrators, vendors, and developers. This need is further highlighted by Zimmermann et al. [77] who showed that vulnerabilities in widely-used open-source libraries impacted numerous software products. Unfortunately, the current state-of-the-art in security and privacy vulnerability notification only considers singlular stakeholders. Similarly, in fintech, Abdou et al. [78] showed that inadequate API security could expose critical consumer financial data, impacting multiple stakeholders including consumers, banks, developers, and regulators in open banking ecosystem. Our work provides a model for testing the effectiveness of vulnerability notifications in these multi-stakeholder ecosystems.

Multi-stakeholder notification research warrants more attention. Research on multi-stakeholder supply chains is complicated due to stakeholder inter-dependencies and mixed incentives. These complexities raise questions about which stakeholder to notify and how to notify each one. Our study, using the online advertising supply chain as a case-study, shows that not all stakeholders are equally capable or willing to resolve vulnerabilities. Furthermore, changing notification sources only, significantly influences some stakeholders. This research is the first to tackle this scenario and highlights the need to examine other multi-stakeholder ecosystems.

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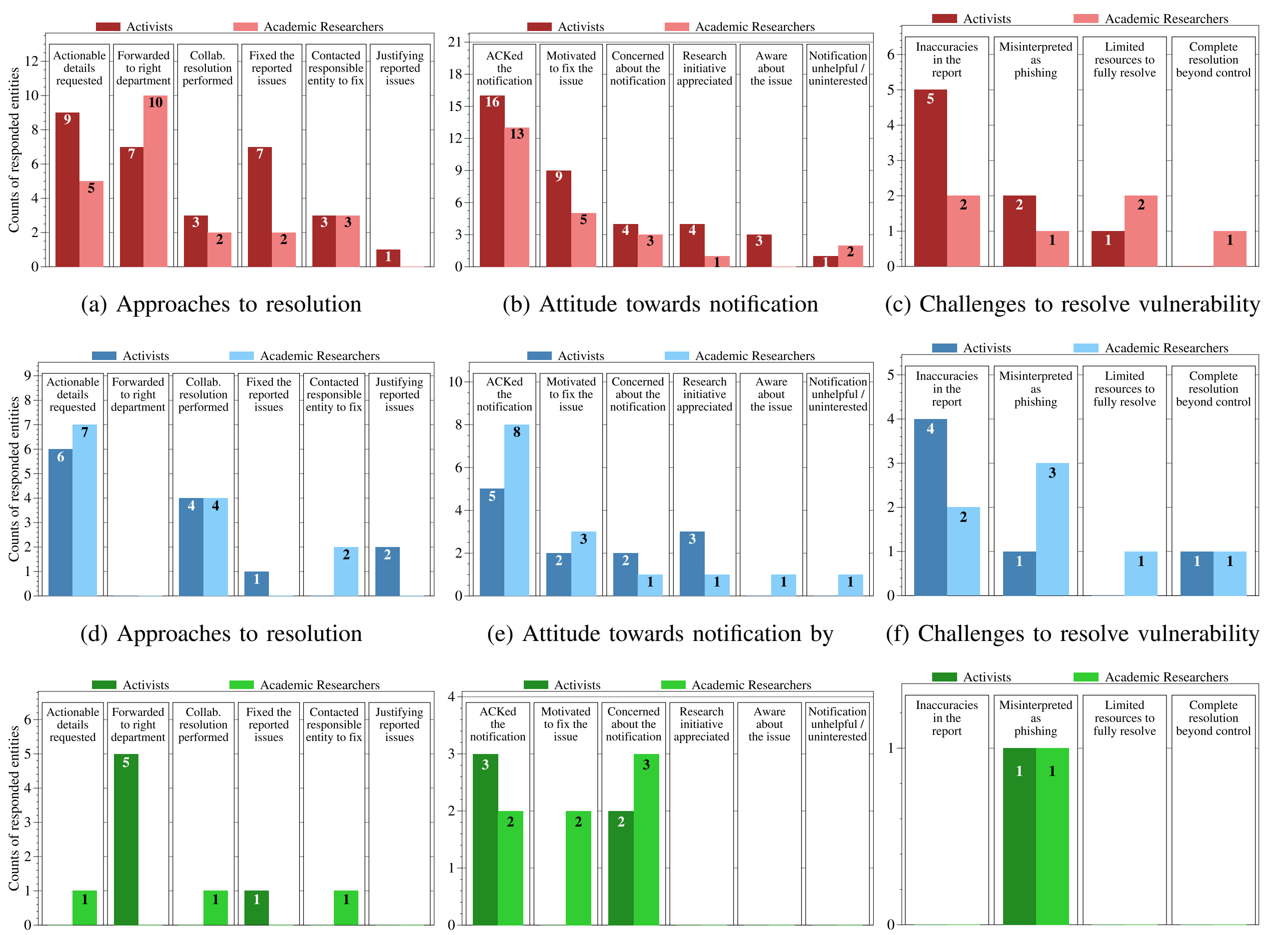
Appendix



(a) Approaches to resolution (b) Attitude towards notification (c) Challenges to resolve vulnerability

(d) Approaches to resolution (e) Attitude towards notification by (f) Challenges to resolve vulnerability

(g) Approaches to resolution (h) Attitude towards notification (i) Challenges to resolve vulnerability

Figure 5: Categorization of notification responses by sender reputation under different themes for `victim publishers` [(a)–(c)], `ad-networks` [(d)–(e)], and `advertisers` [(f)–(h)].