Hoop: Offloading HTTP(S) POSTs from User Devices onto Residential Gateways

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***Abstract*—Mobile users generate ever-increasing amounts of digital data, such as photos and videos, which they upload, while on the go, to online services. 3G connectivity enables mobile users to upload their data while on the go but drains the battery of their devices and overloads mobile service providers. Wi-Fi data offloading overcomes the aforementioned issues for delay-tolerant data. This, however, comes at the cost of constrained mobility for users as they are required to stay within a given area while the data is uploaded. The up-link of the broadband connection of the access point often constitutes a bottleneck and incurs waiting times of up to tens of minutes. In this paper, we advocate the exploitation of the storage capabilities of common devices located on the Wi-Fi access point LAN, typically residential gateways or set-top boxes, to decrease the waiting time. We propose HOOP, a system for offloading upload tasks onto such devices. HOOP operates seamlessly on HTTP(S) POST, making it highly generic and widely applicable; it also requires limited changes on the gateways and on the web server and none to existing protocols or browsers. HOOP is secure and, in a typical setting, reduces the waiting time by up to a factor of 46. We analyze the security of HOOP and evaluate its performance by correlating mobility traces of users with the position of the Wi-Fi access points of a leader ISP. We show that, in practice, HOOP drastically decreases the delay between the time the photo is taken and the time it is uploaded, compared to regular Wi-Fi data offloading. We demonstrate the practicality of HOOP by implementing it on a wireless router.**

I. INTRODUCTION

With the advent of mobile devices, users generate ever-increasing amounts of digital data while on the go. For instance, they take photos and videos with their smartphones and produce or edit possibly large documents on their tablets and laptops. The data is then uploaded (often automatically) to online services, typically through web applications, native apps or system services. They do so for various purposes ranging from social sharing (e.g., sharing photos on Facebook or Flickr, or videos on YouTube) to increased availability and backup (e.g., uploading all sorts of documents to a cloud storage service such as Dropbox or iCloud). In many cases, the upload to the online service is performed through HTTP(S) POST operations (e.g., using a browser, or with applications relying on HTTP-based APIs).

To upload the data they produce while on the go, users rely on the connectivity of their mobile devices, namely 3G and Wi-Fi capabilities. To do so, they are offered essentially two options, both with noticeable drawbacks. Cellular connectivity enables mobile users to upload their data from virtually anywhere (and while moving) but drains the battery of their devices [1], [2] and overloads mobile Internet service providers, which, in response, impose data caps (and either, block the traffic, reduce the bandwidth or over-charge the traffic beyond the limit) much to the detriment of the users. Data offloading at Wi-Fi access points (or 3G DropZones as advocated in [3]), be they public (e.g., AT&T WiFi [4]), business (e.g., Starbucks) or community (e.g., FON [5]) hotspots or personal or corporate access points, overcomes the aforementioned issues for delay-tolerant data. This, however, comes at the cost of constrained mobility and/or significant delays for users. Indeed, the users are required to stay in the close vicinity of the access point while the data is being uploaded. In the case of personal or corporate access points, the data is uploaded only when the user reaches the corresponding location (i.e., home and work place respectively). A determining factor of the upload time is the up-link speed of the Wi-Fi access point's Internet connection (typically 1 Mbps [6]) which often constitutes a bottleneck compared to the Wi-Fi connection (typically 50 Mbps). The waiting time can reach ten minutes for 20 high-definition photos uploaded on a 1 Mbps Internet link.

In this paper, we propose to leverage on the processing and storage capabilities of common devices located on the Wi-Fi access point's local area network (LAN) to implement a sort of store-and-forward HTTP(s) proxy, thus decreasing the waiting time to the point where the Wi-Fi connection of the access point becomes the bottleneck. First-class candidates to implement such a scheme include always-on residential gateways [7], [8], routers, network-attached storage (NAS) units, and set-top boxes. One major design challenge, which is paramount for a wide adoption, is to provide a solution that is completely transparent for the users and that requires as-small-as-possible changes to existing software and protocols. We propose HOOP, a system for offloading upload tasks onto devices such as gateways in a secure and seamless way. In a nutshell, when a user reaches an HTML upload form on a HOOP-enabled website, her browser looks for a device running HOOP on the local network (say a gateway) to offload the uploading task. If such a device is found, the user's browser, instead of directly uploading the file to the online service, encrypts and uploads the file to the gateway, together with an authentication token, at a speed determined by the Wi-Fi connection of the access point. At this point, the user can disconnect from the access point, and potentially move and

switch off her device, while the file is being asynchronously uploaded by the gateway.

HOOP operates seamlessly–from the standpoint of the user–on HTTP(S) POST and relies only on existing web standards (e.g., JavaScript and AJAX) and network protocols (e.g., HTTP(S) and DNS), thus making it highly generic and widely applicable. More specifically, it can be used (through its open API) by any application that relies on HTTP(S) POST to upload data (e.g., HTML forms, Flash/Java uploaders, native apps). HOOP requires only limited changes on the gateways and on the web server and none at the client side (i.e., at the mobile device's operating system and browser). HOOP is secure and it significantly reduces the users' waiting time.

We analyze the security of HOOP and we show that HOOP guarantees the confidentiality and the integrity of the uploaded data, with respect to various attackers including the gateway and eavesdroppers. In addition, we show that HOOP does not create new opportunities for an attacker to disrupt the upload or attack the online service. We evaluate the performance of HOOP in two scenarios. We consider a static user uploading data at a HOOP-enabled Wi-Fi access point and show experimentally that the waiting time is reduced by a factor of 46, compared to regular Wi-Fi data offloading. We consider a mobile user who uploads data while moving, through a network of hotspots, and we show through trace-driven simulations (i.e., by correlating mobility traces with the positions of the Wi-Fi hotspots from a leader ISP), that HOOP increases the upload capacity by a factor of 42. We demonstrate the practicality of HOOP by implementing it on a high-end set-top box and on a wireless router (for the code running on the gateway) and on various websites including a minimal HTML form-based uploader, the Flash and HTML 5 uploaders of the Gallery [9] web photo organizer, and the Java uploader of the ResourceSpace [10] web data management service. Finally, we discuss potential business models for HOOP and show that the involved parties, in particular the users, the online service providers, the Internet service providers (ISP), and the access point operators, all have incentives to adopt HOOP.

The rest of the paper is organized as follows. In Section II, we survey the related work. In Section III, we introduce the system model and we give some background about HTTP(S) uploads. In Section IV, we present and describe HOOP. We analyze the security of HOOP and we report on its performance evaluation in Section V. Finally, we discuss the incentives and the economics behind HOOP in Section VI and we conclude the paper in Section VII.

II. RELATED WORK

The problem of mobile data upload has received a great deal of attention from the research community over the last few years. More specifically, Balasubramanian *et al.* first proposed [11] to augment the 3G capacity in mobile scenarios by exploiting Wi-Fi access points. They implement a software solution for delaying data exchanges and fast-switching between 3G and Wi-Fi, and they assess the potential of their approach. In [1], Lee *et al.* perform a large scale experimental performance evaluation of data offloading over Wi-Fi that demonstrates the benefits of this approach, both in terms of the amount of data offloaded from 3G and of battery power. In [3], Trestian *et al.* study the data generation and upload patterns of mobile users and advocate the use of cells with disproportionally upgraded bandwidth, called Drop Zones, for offloading the content generated by mobile users while on the go. In addition, they tackle the problem of the optimal placement and of the dimensioning of the Drop Zones. In all these piece of work, it is assumed that the data is offloaded directly over Wi-Fi, at the speed of the access point's connection to the Internet, which constitutes a bottleneck. Although HOOP relies on the same approach, i.e., offloading traffic at Wi-Fi access points, it goes beyond by exploiting the storage capacity at the access points to fully take advantage of the Wi-Fi connectivity for delay-tolerant uploads.

Several pieces of work, e.g., [7], [8], advocate the use of the storage capacity of gateways–and other always-on devices with storage capacity–to offload data transfer from user devices. Technical solutions have been proposed and implemented on gateways, set-top boxes and networked area storage units. For instance, many such devices offer HTTP download services and run BitTorrent clients (e.g., Synology NAS). Closer to our work, the Fonera [12] enables users to asynchronously upload files to a number of online services (including YouTube, flickr, and Facebook) by simply copying them over, e.g., ftp, to specific folder. Unlike HOOP, such solutions have major drawbacks that prevent wide adoption in the public domain: The device is trusted with the users' credentials for these online services; the device is given the users' data, in clear, which it can alter; the solution is dependent on the online service (as it relies on their proprietary APIs) and it requires explicit user interactions, as opposed to HOOP that is generic and seamless.

III. SYSTEM MODEL AND BACKGROUND

We consider a system composed of the following entities: (1) a local area network (LAN) connected to the Internet by an ISP, (2) a mobile device, controlled by the user, and (3) an online web service, as described in Figure 1. The local network is composed of a router (typically a gateway) that connects the different devices to the Internet, a device with computational and storage capabilities to run HOOP (typically a set-top box or the gateway), and an access point that allows users with wireless-equipped devices to connect to the local network. The user connects to the Internet (through the local network) with her wireless-equipped mobile device and makes use of web services through her installed browser and native apps. We consider an online web service that allows users to upload data through HTTPS[1] POST operations, from an HTML form (potentially with AJAX), a Flash uploader, or a native app. Throughout the paper, we focus on the case of HTML forms,

[1]We focus on HTTPS throughout the paper: The case of unsecured HTTP can be solved by implementing a proxy at the IP level; this is not possible for HTTPS, as TLS layer protections rely on session keys that are periodically renewed.

the other cases being in fact simpler as the service provider controls the application, whereas for HTML forms the service provider does not control the browser.

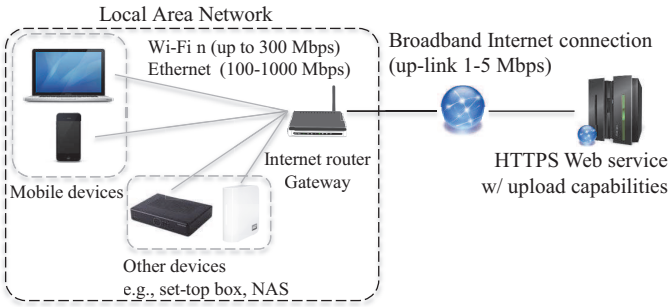


Fig. 1. Setup of Hoop.

In a typical HTML scenario (without HOOP), a user connects to the web service and requests the upload page, through HTTP(S), from the browser installed on her mobile device. The web service returns a HTML web-page including a form (e.g., see Figure 2) that contains at least a form element to select the data (typically some files, e.g., photos) to be uploaded, some extra information (e.g., a caption), an authentication token, and the target page (https://www.service.com/post.php) to which the data will be posted. The user then selects the file(s) to upload and submits the form by clicking on the corresponding button, and the data is posted to the target page (typically a php page). The user must stay connected until the data is uploaded. Once the data is uploaded, the target pages checks that the user is authenticated (e.g., based on an authentication token stored in a hidden field of the HTML form) and it retrieves and processes the data (e.g, adds the photos to the user's profile in the service's database); then a message confirming the upload is shown to the user. The whole process is depicted in Figure 3.

```
<form id="upload_form" action="post.php" method="post"
    >
  <input type="file" name="data">
  <input type="text" name="caption">
  <input type="hidden" value="..." name="token">
  <input type="button" value="Upload"
         id="upload_button" onclick="upload_form.submit
             ();">
</form>
```

Fig. 2. HTML upload form.

Consider the typical scenario of a native mobile application, written in Java, for the Android platform. The application communicates with the web service through HTTP(S) in order to use the same interface as for the website: The application collects data from the local file system, as well as from various elements of the graphical user interface (GUI); the application embeds the data in an HTTP(S) request that it POSTs to the target URL (e.g., https://www.service.com/post.php) by using a dedicated library (e.g., `org.apache.http.client`).

IV. HOOP

In this section, we describe HOOP, a system for offloading upload tasks onto devices located on the same LAN as the user's mobile device in a *store-and-forward* fashion. HOOP involves three different entities as described in the system model: a software component on the device running HOOP (say a gateway) the application running on the user's mobile device, and the web service. We describe the functioning of HOOP by listing and explaining the different operations performed by each of the three aforementioned entities. HOOP operates as follows: the mobile device (be it a script executed by the browser or a native app) searches for a device running HOOP on the local network and, if any such device is found, it processes (i.e., re-formats and encrypts) the data to be sent and directs the upload to this device (instead of to the web service). The device running HOOP stores the data received from the mobile device and asynchronously uploads it to the web service that handles the data as for a regular upload. We first describe the general functioning of HOOP, depicted in Figure 5; then we describe the specifics of its implementation on the mobile device as a web application running in a browser and as a native app.

A. System Description

The HOOP component running at the gateway essentially consists of a daemon acting as both an HTTP server bound to a fixed pre-defined port and an HTTP client. At the startup, the HOOP component registers the hostname `hoop.local` on the local network through the DHCP protocol [13]. Note that as gateways often host a DHCP/DNS server, the hostname registration can be done locally and the gateway can make sure that no other device on the LAN registers as `hoop.local`. The HTTP server implemented by the HOOP component can be accessed at `http://hoop.local/` and offers two services: `test` (accessible at `http://hoop.local/test`[2]) that allows devices on the LAN to detect its presence and test its availability, and `offload` that implements the store-and-forward operation, as we describe below. In order to allow scripts originating from HOOP-compatible web services to connect to the gateway's HTTP services, the latter implements a cross-origin resource sharing (CORS [14]) policy by adding the rule `Access-Control-Allow-Origin:*` to the HTTP header (or a similar rule in the `crossdomain.xml` file for Flash applications).

The HOOP-compatible web service hosts, in addition to the traditional page `post.php`, a page `post_hoop.php` that handles the uploads which are offloaded to and forwarded by the HOOP component running at the gateway. Although these two pages differ in the way they retrieve and pre-process the uploaded data, they process this data in the same way by relying on the same `php` function. Thus, the modifications required at the web service are limited. The web service has a secret key K_{ws} for symmetric authenticated cryptography. Upon login, the mobile device obtains an authentication token T from the web service. When an upload operation is initiated,

[2]Note that we omit the port for the sake of clarity.

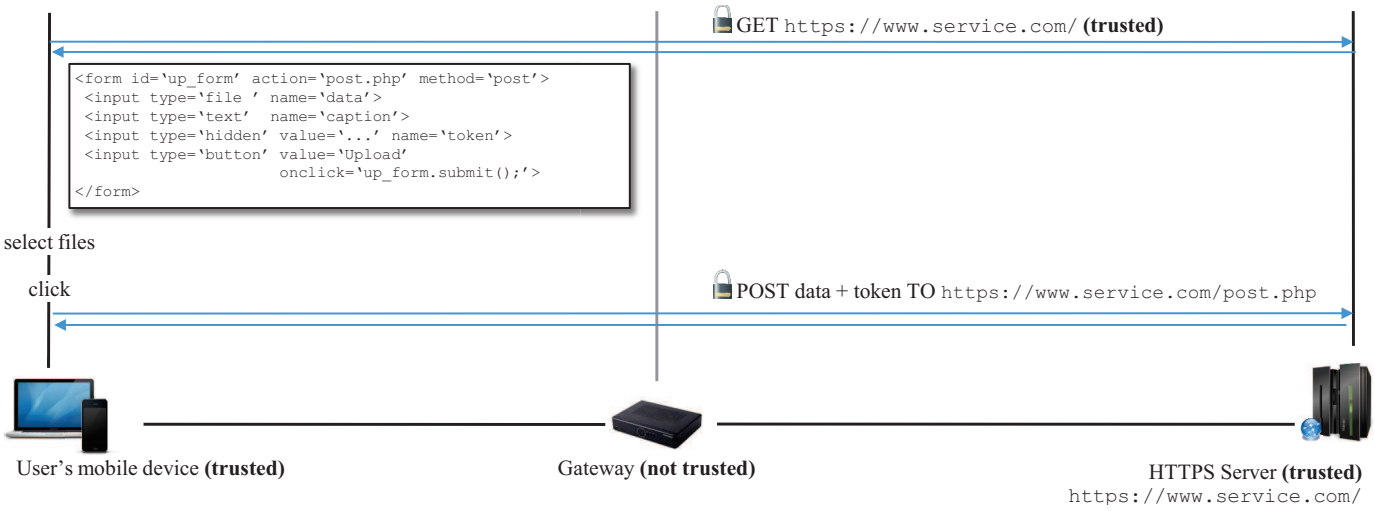


Fig. 3. System overview without Hoop.

the mobile device obtains a fresh random secret key K for symmetric authenticated encryption, together with a version of the key encrypted with the secret key of the web service, i.e., $E_{K_{\text{ws}}}(K)$ where E denotes the encryption operation (typically AES in OCB, CCM or EAX mode), from the web service.

The mobile device (i.e., a web-application running in the browser, a Flash application, or a native app) searches for a device running HOOP on the local network by sending an HTTP request to `http://hoop.local/test`. If the request returns successfully (i.e., the host `hoop.local` is resolved and found, and the request returns the HTTP success code 200–the gateway returns the HTTP service unavailable 503 code if its upload buffer is full), the mobile device sets the target URL to http://hoop.local/offload, so as to offload the upload to the device running HOOP, sets a GET parameter to the target URL of the web service (i.e., http://www.service.com/post_hoop.php), and generates the following post data: $Z = E_{K_{\text{ws}}}(K) \mid\mid E_K(T \mid\mid D)$, where E denotes the encryption operation (e.g., AES in OCB, CCM or EAX mode), T is the authentication token provided by the web service, and D is the data the user wants to upload (e.g., a photo and a caption). Note that as the content sent by the mobile device to the device running HOOP and by the device running HOOP to the web service is encrypted, there is no need to use TLS encryption (i.e., HTTP suffices); this alleviates the need for certificate management at and for the gateway. Finally, the mobile device posts the data Z to the offload URL http://hoop.local/offload. As the mobile device and the device running HOOP are on the same local network, the speed at which the data is transferred is determined by the technology used on the LAN (typically 100/1000 Mbps Ethernet or Wi-Fi g/n/ac) but is independent from the speed of the Internet connection.

When the gateway receives a request to its `offload` service, it first extracts the target URL of the web service from the GET parameters (i.e., http://www.service.com/post_hoop.php). Then it extracts the POST data (i.e., $E_{K_{\text{ws}}}(K) \mid\mid E_K(T \mid\mid D)$) and passes this data to its HTTP client that (re-)posts the data to the target URL of the web service. When the device running HOOP has limited processing and memory capabilities (e.g., a wireless router as described in Section V), the HOOP component is implemented as a standalone native executable file that provides basic HTTP server and client features for receiving and (re-)posting offloaded data. When running on a more powerful device (e.g., a set-top box, a NAS, a dedicated server), the HOOP component can also be integrated into an existing HTTP server, e.g., as a module in the Apache HTTP server.

The `post_hoop.php` page hosted by the web service parses the POST data. It first obtains the symmetric key K by decrypting $E_{K_{\text{ws}}}(K)$ with its secret key K_{ws}. Then, it decrypts the data and the authentication token by using the key K and passes them to the script used to handle regular uploads (i.e., those that do not make use of HOOP). Note that when decrypting the different parts of the POST data, the php script checks the integrity of the data and drops the request if it fails the integrity test. Figure 4 gives a simplified version[3] of a typical `post_hoop.php` page (note that any language, such as Java or Python could be used for implementing the `post_hoop`). Note that the web service relaxes its CORS policy for the `post_hoop.php` page by accepting any origin for this page.

B. Implementation

The implementation of HOOP as a native app on the mobile device is straightforward: preparing and sending HTTP requests is achieved by using a dedicated library such as `org.apache.http.client` for Java on Android; the encryption is performed by using a dedicated library as well, e.g., `javax.crypto`. The authentication token and the encryption key are obtained from web service through HTTP (e.g., returned in the XML or JSON format).

[3]For the sake of clarity, the snippets do not exactly match the actual implementation. In particular, we omit error-handling code as well as diverse optimizations.

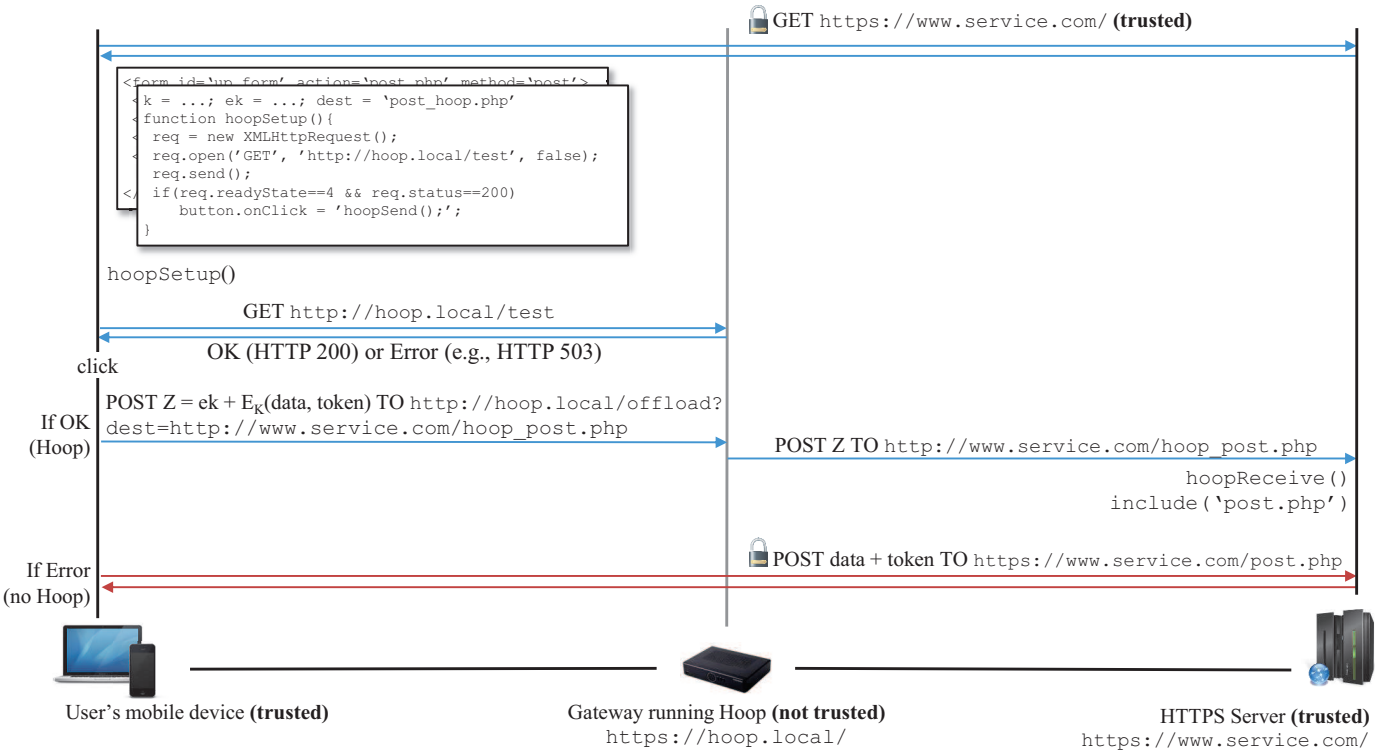


Fig. 5. System overview with Hoop

```
function hoopReceive(){
    $fd = fopen("php://input", "r")
    $k = hoopReadAndDecipherSessionKey($kws,$fd)
    $data = hoopDecipher($k,$fd)
    list ($_POST, $_FILE) = hoopMultipartDecode($data)
}
hoopReceive();
include("post.php");
```

Fig. 4. Hoop upload php script.

The implementation of HOOP as a web application however, is challenging as the web application runs within the browser over which the developer has no control. The code executed by the browser is provided by the web service as a JavaScript. The script contains, in two variables, the symmetric key K and its encrypted version $E_{K_{\text{ws}}}(K)$. When the JavaScript is loaded, it searches for a device running HOOP by making an asynchronous XMLHttpRequest to http://hoop.local/test. If the request returns successfully, the JavaScript modifies the upload form in order to offload the upload to the device running HOOP. This is achieved by setting the target URL of the HTML form (i.e., its action attribute) to the empty string, and by setting instead, through the onsubmit attribute of the submit button, a JavaScript function to be executed when the form is submitted (see Figure 6). This function accesses the data from the files through the HTML 5 File API, performs the encryption by using a dedicated JavaScript library[4] (e.g., crypto-js [16]), and it sends the encrypted POST data to the device running HOOP at http://hoop.local/offload by making an XMLHttpRequest with the GET parameter set to the target URL of the web service (see Figure 7). When the upload terminates, the user is redirected to a dedicated web page by changing the location header.

```
button = document.getElementById("upload_button");

function hoopSetup(){
  // search for a device running Hoop
  req = new XMLHttpRequest();
  req.open("GET", "http://hoop.local/test", true);
  req.onreadystatechange=function(){
    if(req.readyState==4 && req.status==200){
      // switch the upload method to Hoop
      button.onClick = "hoopSend();";
    }
  }
  req.send();
}
```

Fig. 6. Hoop JavaScript function for activating Hoop, if a device running Hoop is found on the LAN.

[4]Note that the W3C is currently working on the specification and the implementation of a JavaScript cryptography API named WebCryptoAPI [15].

```
k = "..."  // symmetric key (in clear)
ek = "..." // symmetric key (encrypted)
dest = "http://www.service.com/post_hoop.php"
form = document.getElementById("upload_form");

function hoopSend(){
  data   = hoopMultipartEncode(form) // extract the data
  cipher = hoopCipher(data, k)       // encrypt the data
  req = new XMLHttpRequest();
  req.open("POST", "http://hoop.local/offload?dest=" +
       urlencode(dest), false);
  req.send(ek + cipher);
  window.location = "...";
}
```

Fig. 7. Hoop JavaScript function for preparing and offloading the data to a device running Hoop.

C. Additional Features

In addition to its core offload functionality, HOOP offers side features that enable users to monitor their offloaded uploads, at the gateway and at the web service. Upon a successful offload onto the gateway, the user is provided with a link of the form `hoop.local/monitor?ID=...`, where ID is a random identifier assigned to the offload, to monitor (i.e., see the current upload status) the (re-)posting of the uploaded data. The operator of the local network can make the monitoring service accessible from outside the LAN; in this case, the local hostname must be replaced by a fully qualified hostname. The monitoring service can be implemented at the web service as well: When an upload is offloaded to a device running HOOP, the web service is notified by the user's mobile device through an HTTPS request including the key K and the meta-data (e.g., the caption and the names of the files). The user can subsequently monitor, through her account on the web service, the list of her offloaded uploads and monitor/control (i.e., pause, resume, stop) them.

Finally, the user can specify, in her account settings on the web service, certain policies to decide whether to use HOOP for offloading her uploads. For instance, the user can decide to never use HOOP, to always use HOOP, or to be asked (through e.g., a check-box) whether to use HOOP when a device running HOOP is found on the local network. More complicated policies can be used so as to, e.g., make the decision based on the sizes and types of the files to be uploaded.

V. EVALUATION

We evaluate HOOP with respect to its security (e.g., the confidentiality and the integrity of the user's data), its efficiency (e.g., technical feasibility of HOOP on various devices), and its efficacy (e.g., in terms of its offload potential). We do not discuss the security of the features mentioned in Section IV-C as they do not constitute the core of HOOP.

A. Security

We look at the security of HOOP by considering different adversarial scenarios. As HOOP is designed for a wide deployment in the public domain, neither the gateway nor the user is trusted, thus they constitute potential adversaries. In addition, we consider (possibly active) adversaries such as a jammer, an eavesdropper, or another user connected to the LAN. We structure our security analysis with respect to the three entities involved in HOOP.

a) Confidentiality and integrity of the users' data: The confidentiality and the integrity of the data (users' data, as well as the key K, and the JavaScript or HTML codes) exchanged directly between the user's mobile device and the web service is guaranteed by the TLS encryption of the HTTPS connection: Neither the router nor an eavesdropper (should it snoop on the LAN or on the Internet) can read or stealthily (i.e., without being detected) tamper with this data. The confidentiality and the integrity of the data exchanged between the user's mobile device and the web service, through the HOOP on the gateway (over unsecured HTTP), is guaranteed by the application-layer encryption (i.e., an authenticated encryption (AEAD) such as AES in OCB, CCM or EAX mode), the encryption key K being known only to the user and to the web service as it is exchanged over HTTPS. The authenticated encryption implements integrity checks that prevent an attacker from tampering with the data. Therefore, an adversary, such as a malicious gateway, cannot tamper with the data $(D||T)$ in the post data as it does not know K.

b) Security of the gateway: An adversary can perform a denial-of-service (DoS) attack against the gateway by issuing a large number of offloading requests. It is in general difficult to defend against DoS attacks, however they are not specific to the use of HOOP; this means that traditional protection mechanisms can be used and that HOOP does not create new opportunities to attack the gateway.

c) Security of the web service: Relaxing the CORS policy for the `hoop_post.php` page exposes the web service to cross-site scripting attacks (XSS), e.g., a third-party website stealthily posting data to this page by relying on an existing authentication cookie in the user's browser. However, as the `hoop_post.php` page authenticates users based on the token T encrypted with the secret key K instead of using cookies, such XSS attacks cannot succeed. Finally, an adversary can carry out a DoS attack against the web service, through HOOP, by offloading a large number of requests on a gateway that runs HOOP. Such an attack, however, does not give more power to the adversary as it is similar to making the requests directly from the LAN.

B. Efficiency

We evaluate the efficiency of the HOOP components running on the mobile device and on the gateway based on a real implementation on various platforms.

d) Mobile device: encryption: Encryption (along with file access and communication) constitutes a potential bottleneck when HOOP runs a mobile device. We considered both OpenSSL and CryptoJS libraries for symmetric AES-256 encryption as they constitute natural candidates for an implementation of HOOP as a native app and as a web

application respectively. We conducted our experiments on three different devices and settings: a laptop (Core i5-2520M) running Chrome 30 on Windows 7, an iPhone 4 running Safari for iOS 7.0, and a Galaxy S3 running Chrome 30 for Android 4.2. The results, summarized in Table I, show that a native app can easily saturate a broadband connection and, in some cases (i.e, Laptop and Galaxy S3), saturate a Wi-Fi connection at 300 Mbps. The results are not as good for JavaScript. However, service providers are most likely to provide native apps on mobile devices (e.g., Dropbox, iCloud, YouTube uploader), and the performance of JavaScript on laptops, which are likely to use the web version of HOOP within the browsers, is good. Furthermore many factors foresee significant improvements for JavaScript encryption: The processing power of smartphones increases rapidly (the iPhone 4 and the Galaxy S3 have been released in 2010 and 2012 respectively and their successors have significantly improved processing capabilities); developers actively work on improving the JavaScript performance of browsers in general; and the WebCryptoAPI [15] specification of W3C could lead to the use of native code for JavaScript encryption for web applications.

Dev. (Lib.)	**Throughput**
Laptop Core i5-2520M (OpenSSL)	640 Mbps
Laptop Core i5-2520M (JavaScript)	58 Mbps
iPhone 4 (OpenSSL)[5]	96 Mbps
iPhone 4 (JavaScript)	5.1 Mbps
Galaxy S3 (OpenSSL)[6]	416 Mbps
Galaxy S3 (JavaScript)	6.5 Mbps

TABLE I
BENCHMARK OF SYMMETRIC CRYPTOGRAPHIC LIBRARIES ON VARIOUS DEVICES (AES-256 ENCRYPTION).

e) Gateway component: offload and upload: We implemented the gateway component in charge of receiving and (re-)posting offloaded data on two different devices: a wireless router running OpenWRT and a set-top box (see Table II for the detailed configuration). The set-top box has similar hardware to a typical NAS. We implemented the HOOP component in C and compiled it to a standalone native executable linked against the `libevhtp` 1.2.6 (static link) and `libevent` 2.0.5 (dynamic link) libraries. The implementation has ∼350 source lines of code (excluding the libraries) that compile to a binary of ∼60 KB (excluding a dynamic library of ∼250 KB) on both platforms. The wireless router embeds a Wi-Fi 802.11n access point and the set-top-box is connected to the router/AP through a 100 Mbps Ethernet network interface.

We conducted our experiments with HOOP running either on the router or on the set-top box and with our Laptop Core i5-2520M connected to the local network either over 100 Mbps Ethernet or over Wi-Fi 802.11n (the actual negotiated link speed was 78 Mbps). Our experiments with a wired connection between the mobile device and the gateway enable us to assess the performance of the HOOP component running at the gateway (as a wireless connection could have constitute a bottleneck), whereas our experiments with a wireless connection enable us to assess the global performance of HOOP as a whole. We used ApacheBench on our laptop to execute HTTP POST requests and collect statistics.

[5]Obtained from http://hmijailblog.blogspot.fr/2011/02/openssl-speed-on-iphone-4.html (Last visited Oct. 2013)

[6]Obtained from https://jve.linuxwall.info/ressources/taf/aesmeasurements.txt (Last visited Oct. 2013)

Dev.	**Arch.**	**Proc.**	**RAM**	**HDD**
Router	MIPS Atheros	AR7241@400 Mhz	32 MB	USB 320 GB
Set-top	x86 Intel	Atom@1.66 Ghz	1 GB	SATA 250 GB

TABLE II
TECHNICAL SPECIFICATIONS OF THE DEVICES USED FOR THE EVALUATION. THESE TWO DEVICES ARE REPRESENTATIVE OF ISP-PROVIDED EQUIPMENTS: A MODEM WITH LIMITED CAPABILITIES AND A HIGH-END SET-TOP BOX.

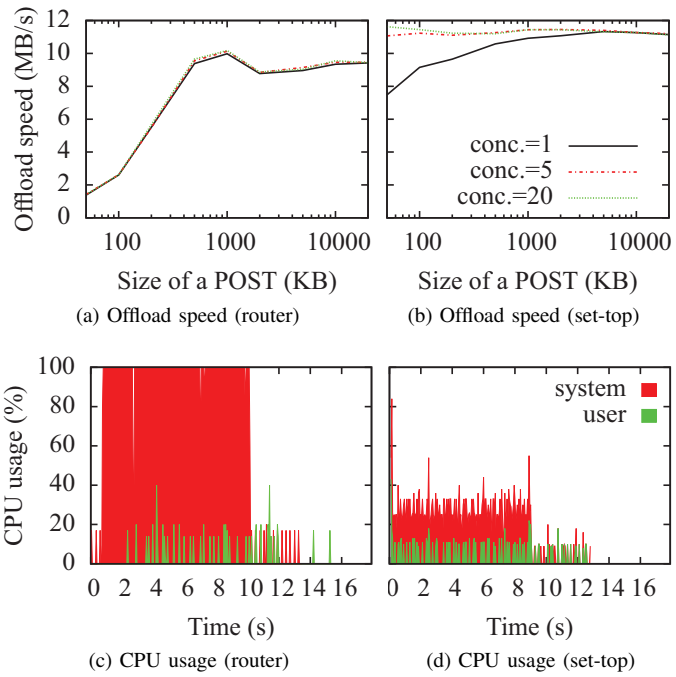
We evaluate the performance of the HOOP component running on the gateway, in a wired setting, along the following metrics: (1) the offload speed (as a function of the size of the POST, for different concurrency levels[7]), and (2) the CPU usage (and the breakdown between system and user time). The results are presented in Figure 8. It can be observed on Figures 8a and 8b that for small POSTs (e.g., 50-200 KB) offloaded onto the set-top box, sending concurrent requests improves the offload speed as the requests are processed concurrently at the gateway, thus amortizing the connection delays. For large POSTs (i.e., > 1 MB), which constitute the main use-case of HOOP, both the router and the set-top box saturate the LAN connection (i.e., Ethernet at 100 Mbps∼12 MBps) at 10 and 11 MBps respectively. The performance of HOOP is not altered when concurrent POST requests are issued. Figures 8c and 8d show that the system accounts for a large proportion of the CPU usage; this means that the CPU usage is mostly devoted to performing I/Os (i.e., reading from and writing to the network and the disk). It can be observed that, unlike for the set-top box, the CPU of the router saturates; this explains the slight performance gap between the two devices, with respect to the offload speed, observed in Figures 8a and 8b.

C. Efficacy

We evaluate the efficacy of HOOP: first experimentally in a static setting where the users do not move and stay connected to the same access point, and then through trace-driven simulations in a mobile setting.

1) Experimental Results: We experimentally assess the global performance of HOOP in terms of the time needed to complete an offload, based on our implementation on a laptop/router as described in Section V-B. This metric reflects the immediate gain of a user in a static setting, as it corresponds to the time after which the user can switch off her mobile device and/or start moving out of the range of the Wi-Fi access point. For the web service, we enhance the Gallery [9] web

[7]Browsers can issue requests in parallel by opening up to 6-8 concurrent connections.



(a) Offload speed (router) (b) Offload speed (set-top)

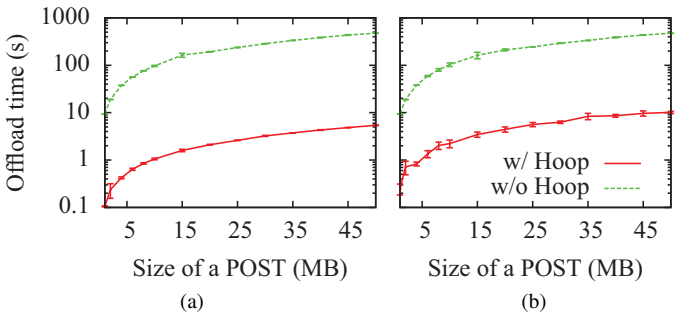
(c) CPU usage (router) (d) CPU usage (set-top)

Fig. 8. Performance of the Hoop component running at the gateway. CPU usage is for POSTs of size 1,000 KB with a concurrency level of 1.

photo organizer with HOOP compatibility[8], and we host it on a server connected to the Internet through a dedicated symmetric connection at 100 Mbps. The local network is connected to the Internet through an ADSL broadband connection synchronized at 12 Mbps (down)/1.15 Mbps (up). Neither the LAN link nor the broadband link has background traffic (i.e., other applications that use the links). Figure 9 shows the results for different POST sizes ranging from 1 to 50 MB in wired and wireless settings (for the connection between the mobile device and the gateway), with and without HOOP. It can be observed that HOOP significantly outperforms regular Wi-Fi offloading (i.e., without HOOP): The offload time is reduced by up to a factor of 85 in a wired setting and by up to a factor of 46 in the wireless settings. These factors roughly correspond to the ratios between the LAN and the broadband link speeds ($100/1.15 \approx 84$ for Ethernet; the observed speed for Wi-Fi 802.11n is consistent with the actual speed of a link at 78 Mbps taking into account the MAC and TCP overheads).

2) Trace-Driven Simulations Results: We evaluate, through trace-driven simulations, the efficacy of HOOP in the scenario of a mobile user, equipped with a Wi-Fi/3G-enabled device, moving in a region covered by a community/commercial network of Wi-Fi access points and a 3G network. When the user is in the range of an access point of the network, it connects automatically to it; this is usually done by the mobile OS (e.g., through the EAP-SIM [17] protocol for AT&T [4] or Swisscom [18] hotspots) or by a dedicated app (e.g., the FON app [5] that uses the user's credentials). In addition, the

[8]We implemented HOOP on ResourceSpace [10] as well to demonstrate HOOP's feasibility for Java-based uploaders.



(a) (b)

Fig. 9. Global performance of HOOP compared to the baseline in a (a) wired and (b) wireless setting.

user could have 3G data plan that enables her to connect to the Internet from anywhere in the region.

a) Dataset: The evaluation is based on a dataset of Wi-Fi access points from the FON network [5]. FON is a large community network with over 10 million hotspots worldwide (most of them are located in Belgium, France, Japan, Portugal, and the UK–and soon in Germany and in the Netherlands – due to to strategic partnerships with leader national ISPs). The access points composing the FON network are mostly routers and set-top boxes provided and operated by the ISPs that hold total control over them (through automatic firmware updates); as such, they constitute first-class candidates to run HOOP. Users who host a FON access point at their home places or pay a subscription can connect (automatically) to the FON hotspots through a dedicated mobile app. The map of FON hotspots is available at `http://corp.fon.com/maps`. In early 2013, we collected the geographic coordinates of the Wi-Fi access points from SFR, a leader French ISP, that is part of the FON network. In urban and residential areas, the density of the network ranges from hundred to more than a thousand of hotspots per square kilometers. In Paris, France, the average density is 853 ± 346 APs/km^2; 47% of the area is covered by at least one access point and the number of visible access points in covered areas is 2.75 ± 1.86 on average, assuming a communication range of 25 m.

In order to build connectivity traces, we correlate the coordinates of the Wi-Fi access points with mobility traces from users moving in the Paris area, France. Our dataset comprises two types of traces: *touristic* paths and *commuter* paths. The first corresponds to pedestrians who explore the city by hopping from one point of interest to another (including the Eiffel Tower, Notre-Dame, and the Arc de Triomphe); the latter corresponds to workers who commute between their homes and their work places using the street public transport system (i.e., bus and tram).

b) Methodology: We developed a trace-based discrete-event simulator to compute the various metric along which we evaluate HOOP. The mobility traces provide discrete samples of the user's position over time. We model the communication range of the access points with a fixed-radius (i.e., R) disc and we use a simple connectivity model. Initially, users are connected to the closest access point in their range: in practice,

this would correspond to the visible access point with the strongest received signal strength indication (RSSI), if any. While a user remains in the range of the access point her device is connected to, it does not change access points. As a users moves out of the range of the access point her device is connected to, the connection is interrupted and her device connects to the visible access point with the strongest RSSI, if any. Connecting to a new access point is assumed to take a constant time δt. When connected to an access point, a mobile device can communicate with the access point (and the devices on the same local network) at speed b_{LAN} and the devices on the local network (including the mobile device) can communicate with remote Internet hosts at speed b_{WAN}. We assume that there is no background traffic on the LAN and on the Internet connection, and that the upload buffers of the gateways are empty. We denote by b_{3G} the speed of the 3G connection. Users from touristic traces generate photos of size S_{pic} at a rate $r_{\text{pic}}^{\text{go}}$ while moving, and at a rate r_{pic}^{POI} while at a point-of-interest. Users from commuter traces generate documents (or edit documents and upload the modified versions, e.g., to Dropbox or iCloud) of size S_{doc} at a rate r_{doc}. The generated files are stored in a buffer on the mobile device and uploaded to a web service in first-in first-out order. When the connection to an access point is lost, the on-going upload is aborted and it is restarted when the mobile device establishes a new connection. Table III summarizes the different simulation parameters together with a brief description and the value used in the evaluation.

We consider the following connectivity scenarios and upload strategies:

- **Wi-Fi only (always mobile)**: Users always move according to their mobility trace and upload their data (w/ or w/o HOOP) over Wi-Fi whenever they are connected to an access point.
- **Wi-Fi + 3G (always mobile)**: Users always move according to their mobility trace and upload their data (w/ or w/o HOOP) over Wi-Fi whenever they are connected to an access point, and otherwise over 3G.
- **Wi-Fi (mobile + static)**: Users move according to their mobility traces and upload their data (w/ or w/o HOOP) over Wi-Fi whenever they are connected to an access point. When connected to an access point, users move only when their upload buffer is empty (i.e., they wait until their upload buffers are empty before moving).

c) Metrics: We assess the performance of HOOP according to the following metrics, that reflect together the gains and costs of using HOOP for the mobile users, in different scenarios:

- **Per-session Wi-Fi offload capacity**: The maximum amount of data a mobile user can offload/upload over Wi-Fi during the connection time at an access point.
- **Total Wi-Fi offload capacity**: The maximum amount of data offloaded/uploaded over Wi-Fi (i.e., assuming that the upload buffer on the user device is never empty).

[9]We estimated the value of this parameter experimentally.

Param.	Description	Value
R	Wi-Fi communication range	25 m
δt	Wi-Fi connection establishment delay[9]	10 s
b_{WiFi}	Wi-Fi connection speed	30 Mbps
b_{3G}	3G connection speed (upload)	0.8 Mbps
b_{WAN}	Broadband connection speed (upload)	1.15 Mbps
S_{pic}	Picture size	3 MB
S_{doc}	Document size	1 MB
$r_{\text{pic}}^{\text{go}}$	Picture generation rate (on-the-go)	0.2/min
$r_{\text{pic}}^{\text{POI}}$	Picture generation rate (at POIs)	5/min
r_{doc}	Document generation rate (e.g., auto-save)	1/min

TABLE III
SIMULATION PARAMETERS: DESCRIPTION AND VALUES.

- **Delay**: The delay between the time a file is generated (e.g., the photo is shot) and the time it is uploaded on the web service.
- **Wi-Fi usage**: The amount and the fraction of data uploaded to the web service over Wi-Fi and the time spent uploading it.
- **3G usage**: The amount and the fraction of data uploaded to the web service over 3G and the time spent uploading it (in the Wi-Fi + 3G scenario).
- **Waiting time**: The time spent waiting for the offload or upload to complete (in the Wi-Fi: mobile + static scenario).

d) Results: Figure 10 shows the Wi-Fi offload capacity per session. This metric is directly proportional to the duration of the Wi-Fi sessions while moving. It can be observed that without HOOP, the 95-th percentile of the amount of data a user can upload is 4.9 MB for the touristic trace (more than the size of a photo) and 0.93 MB (less than the size of a document). This means that, without HOOP, the users from the commuter trace cannot complete any document upload. Finally, we note that the capacity is significantly higher (i.e., $\times 5$) for the touristic trace than for the commuter trace; this is because users from the touristic trace move more slowly than for the commuter trace (pedestrian vs. public transportation passengers), thus the sessions are longer.

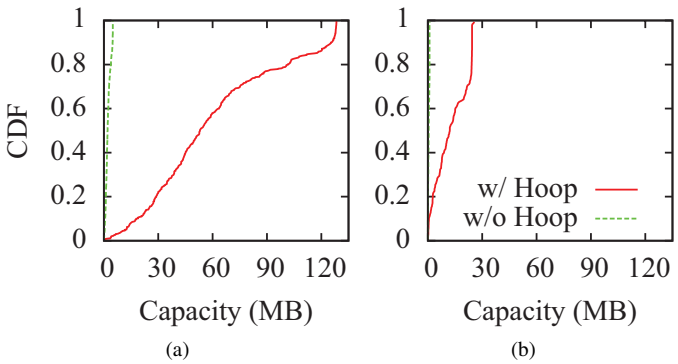


Fig. 10. Wi-Fi offload capacity per session for the (a) touristic and the (b) commuter traces.

We now look at the total Wi-Fi offload capacity, i.e., the total amount of data that is offloaded over Wi-Fi, assuming

that mobile users have an infinite number of files to upload, normalized by the total time of the simulation. Note that this metric takes into account only the amount of *useful* offloaded data: the offloads that are aborted due to Wi-Fi connection loss are *not* taken into account. We also look at the total upload capacity, that takes into account only the amount of data that is actually uploaded to the web service during the time of the simulation. It can be observed that the offload and upload capacities are zero for the commuter trace. This is because the Wi-Fi sessions are too short to upload even a single document (as shown in Figure 10). Finally, we can observe that for the touristic trace HOOP increases the upload capacity by a factor of 42 and the offload capacity by a factor of 45. Note that the upload capacity with HOOP is significantly higher than the speed of the Internet link (i.e., 1.15 Mbps), which corresponds to the upload capacity in a static scenario where the users stay connected to the same access point during the entire experiment. This is because mobile users offload their data on different access points; therefore the uploads are performed simultaneously, thus increasing the total upload capacity.

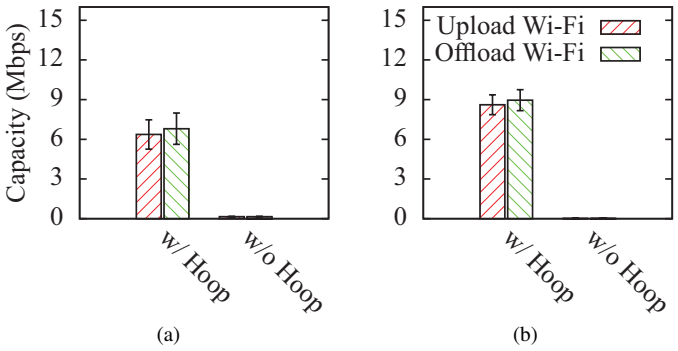


Fig. 11. Total Wi-Fi upload and offload capacities for the (a) touristic and the (b) commuter traces.

Figure 12 shows the cumulative distribution functions (CDF) of the delay in the different connectivity scenarios. For the commuter trace, the CDF is not visible for the "w/o HOOP, always mobile" scenario as the delays are very long. This is because the Wi-Fi connection sessions are too short to enable the user to upload a single document. It can be observed that the delays are drastically reduced with HOOP. Surprisingly, we observe shorter delays "w/ HOOP always mobile" scenario than for the "mobile + static" (i.e., Wait) scenarios. This is because in the mobile scenario, users offload the different files in their buffers to different access points. Hence, the files are uploaded simultaneously, whereas in the wait scenario, the files are uploaded sequentially as they are all offloaded at the same access point. Finally, the results show that 3G connectivity helps reducing the delays. This is because it enables the user to upload some of the files as soon as they are produced while the user stays at a point of interest with no Wi-Fi coverage.

We now look at the active time (i.e., the time spend uploading/offloading data over Wi-Fi or 3G). Figure 13 summarizes the results for different scenarios: it can be observed that

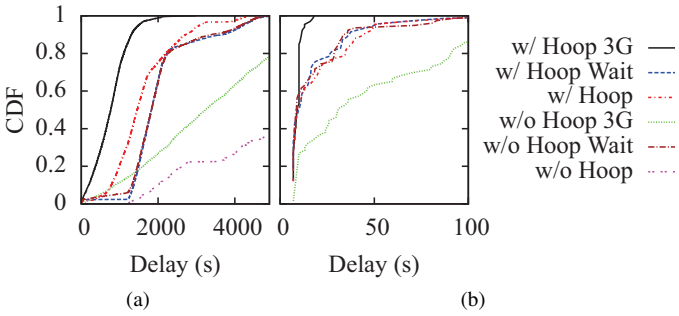


Fig. 12. Delay between the content generation and the upload in different connectivity scenarios for the (a) touristic and the (b) commuter traces.

HOOP consistently decreases the active time while increasing the amount of data offloaded. This is consistent with the increase of the amount of data sent over Wi-Fi (and the decrease of the amount of data sent over 3G). This translates into energy savings as the consumption per MB is lower for Wi-Fi than for 3G [2]. Note that the results from the two traces are not directly comparable as the traces have different durations, and that the users generates files of different sizes, at different rates. Note also that for the same trace, the duration of the experiment is longer in the "Wait" scenario. In our simulations, the waiting periods increase the duration of the experiment by 8% with HOOP, and by 106% without HOOP, for the touristic trace.

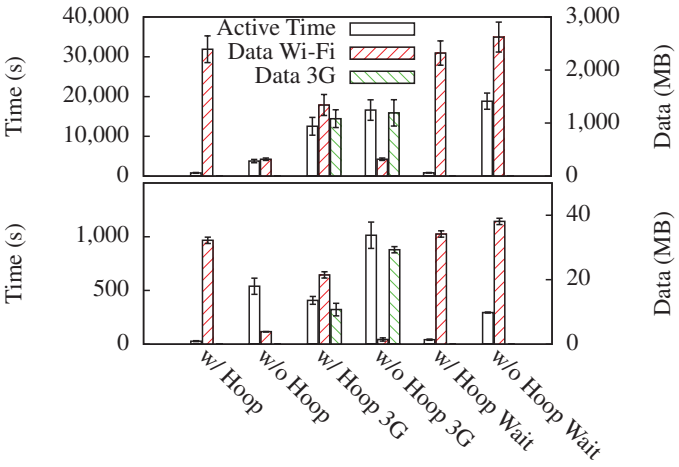


Fig. 13. Time spent sending data and amount of useful data uploaded/offloaded over Wi-Fi and 3G for the touristic (top) and the commuter (bottom) traces.

Finally, we evaluate the energy consumption of the data uploads in different scenarios. To do so, we rely on the values of energy consumption of smartphones network interfaces from [2] (including active time and scan energy consumption for Wi-Fi), summarized in Table IV. We further assume that smartphones perform 1-second scans every 8 seconds. We show the results in Figure 14. It can be observed that HOOP consistently reduces energy consumption. The first reason is that the amount of aborted data uploaded (hence the amount of wasted energy) is reduced with HOOP. Secondly, in the case

	Transfer (J/MB)	Idle (W)	Scan (W)
Wi-Fi	5	0.77	1.29
3G	100	0	0

TABLE IV
ENERGY CONSUMPTION OF SMARTPHONES NETWORK INTERFACES [2].

where 3G is used when there is no Wi-Fi connectivity, HOOP also reduces the energy consumption. This is due to the fact that HOOP offloads larger amounts of data over Wi-Fi (because it offloads data at a higher speed); therefore it uploads lower amounts of data over 3G (which is more energy consuming that Wi-Fi). We can also observe the price to pay, in terms of energy consumption, for the delay improvement brought by the use of 3G connectivity (shown in Figure 12).

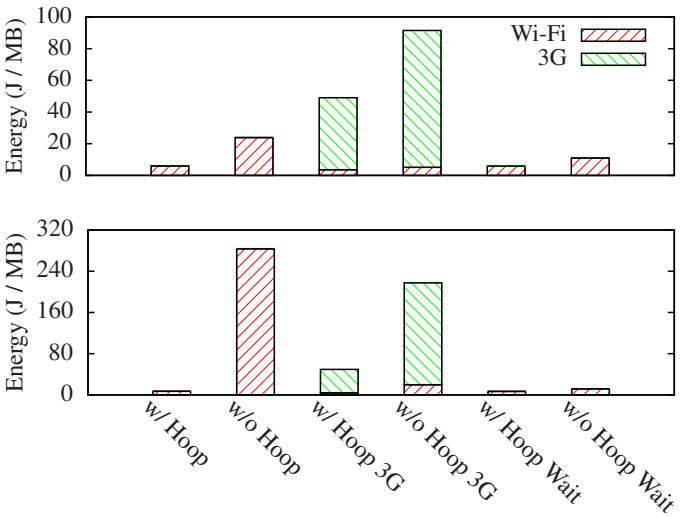


Fig. 14. Energy consumptions for data upload, per sent KB, over Wi-Fi (incl. active time and scans) and 3G for the touristic (top) and the commuter (bottom) traces.

VI. DISCUSSION

In this section, we discuss the incentives for the users to use HOOP; and the incentive and the costs, for the commercial parties involved (e.g., the web service), to implement and to deploy HOOP. These factors are key to its wide deployment and adoption. We also discuss additional features that can make HOOP more attractive to the different parties.

HOOP is beneficial for the users, as shown in Section V-C, and it does not require any user intervention as it operates seamlessly. As such, HOOP increases the brand/product value (1) of gateway/access point/NAS/set-top box manufacturers, (2) of the ISPs that provide gateways and/or set-top-boxes to their subscribers, and (3) of Wi-Fi access point (network) operators. The cost of deploying HOOP on such devices is minimal: The implementation is simple (∼350 source lines of code) and can be easily deployed via (automatic) firmware updates or via third-party applications available on specific repositories (e.g., optware packages and Synology's third-party packages [19]). The fact that HOOP is generic, and thus can be used by any web service, alleviates the need for the manufacturers and third-party application developers to implement ad-hoc solutions for each service (e.g., YouTube, flickr, Picasa and Facebook uploaders implemented on the Fonera [12]). HOOP constitutes an interesting marketing argument for service providers as well and offers them an efficient ready-to-use solution that requires only limited changes to the web service. Furthermore, HOOP offers a unique opportunity for ISPs and service providers to control a fraction of their traffic as they can delay the HOOP uploads. This enables them to smoothen the traffic peaks hence reducing the investments for dimensioning their equipment, as well as their bandwidth costs in the case where burstable billing (e.g., 95-th percentile [20]) is used. Finally, should the use of HOOP be more beneficial to the web service than for the ISP, the web service could pay the ISP for the offloaded uploads, either directly (i.e., in currency) of through advertisement. For instance, one can envision a business model in which the photos uploaded to Facebook through HOOP are displayed with an icon "Uploaded by a Synology NAS" or "Uploaded from AT&T WiFi".

VII. CONCLUSION

In this paper, we presented HOOP, a system for offloading data uploads on devices with storage capabilities, e.g., gateways, in a store-and-forward fashion. Our system enables mobile users to fully exploit the Wi-Fi link by relaxing the speed constraints due to the link that connects the LAN to the Internet. Unlike existing systems, HOOP operates transparently–from the stand point of the users–and provides a ready-to-use, secure and generic solution to data uploads offloading: The mobile users are not required to trust the gateway with their credentials and the gateway can neither see nor alter their data. We reported on our performance evaluation of HOOP, which demonstrate its efficiency and its efficacy: HOOP can run on devices with very limited capabilities (e.g., MIPS processor at 400 MHz with 32 MB of RAM) and decreases the waiting time of mobile users by up to a factor of 46. We intend to conduct a real-world field experiment to further assess the upload performance of HOOP as well as the potential energy savings. In addition, we plan to perform a sensitivity analysis to study the effect of the different parameters on the performance of HOOP.

VIII. ACKNOWLEDGMENTS

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