# Integration of the Captive Portal paradigm with the 802.1X architecture

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#### Abstract

In a scenario where hotspot wireless networks are increasingly being used, and given the amount of sensitive information exchanged on Internet interactions, there is the need to implement security mechanisms that guarantee data confidentiality and integrity in such networks, as well as the authenticity of the hotspot providers.

However, many hotspots today use Captive Portals, which rely on authentication through Web pages (thus, an application-level authentication approach) instead of a link-layer approach. The consequence of this is that there is no security in the wireless link to the hotspot (it has to be provided at upper protocol layers), and is cumbersome to manage wireless access profiles (we need special applications or browsers' add-ons to do that).

This work exposes the weaknesses of the Captive Portals' paradigm, which does not follow a unique nor standard approach, and describes a solution that intends to suppress them, based on the 802.1X architecture. This solution uses a new EAP-compliant protocol that is able to integrate an HTTP-based registration or authentication with a Captive Portal within the 802.1X authentication framework.

**Keywords**: Wireless networks, 802.11, hotspots, Captive Portals, linklayer security, 802.1X, EAP, TLS

### 1 Introduction

The security of 802.11 (Wi-Fi) wireless networks is defined by several standards, such as 802.11i [28] and 802.11w [29]. These standards define a wide range of security mechanisms, including mutual authentication between a user and a network provider and link-layer data encryption and frame integrity control. Furthermore, these standards also open the path to evolution, namely to the development of new, innovative authentication protocols. This is achieved with the adoption of the 802.1X authentication architecture [30], which allows different EAP (Extensible Authentication Protocol [1]) compliant authentication

protocols to be defined and deployed for tackling special requirements [9]. A common characteristic of all these protocols is that all of them produce a secret, shared session key that will be used by 802.11i and 802.11w protection mechanisms to provide an effective security at the link layer.

One of the limitations of the actual, standard 802.11 security paradigm is that it does not support the enrollment of new users by a network. In fact, it supports the protection of users that already share some access credentials with the network provider, but not the setup of those credentials. This is a notorious limitation, since in many cases users could benefit of using a Wi-Fi network that is provided where they are, but they need first to enroll in that network using some sort of alternative communication channel.

Captive Portals did the trick, and because of that, they became very popular to deploy the so-called Wi-Fi hotspots. With Captive Portals, the users may enroll on network providers using a Web browser and the network of interest, and then use the same Captive Portal to authenticate themselves prior to use the network. Recently Cisco forecast in a White Paper [6] that "the total public Wi-Fi hotspots (including homespots) will grow four-fold from 2017 to 2022", which means that the exploitation of Captive Portals will continue to grow.

However, the exploitation of Captive Portals has several drawbacks. First, they are implemented today as an ad hoc, Web-based Man-in-the-Middle (MitM) hack that causes confusion in client systems and users [25, 46, 47]. Second, the Captive Portals' authentication is performed at the applicational level, and thus does not produces key material for being used by 802.11i and 802.11w. Therefore, users accessing Wi-Fi networks controlled by Captive Portals are not protected at the link layer. The consequence is that both users and access networks can be easily attacked and abused in many different ways, which we will detail later (see Section 3). Therefore, they are dangerous when it comes to the transmission of sensitive information, as alerted by several non-technical online publications [10, 45, 36].

### 1.1 Contribution

In this paper, we propose an alternative to the actual Captive Portals. Our alternative keeps their benefit (enrollment of new users with a Web service) while exploring the existing Wi-Fi security mechanisms defined in 802.11i and 802.11w. This alternative explores a new EAP protocol, nicknamed EAP-SH (EAP for Secure Hotspots) and relies on modified end-entities that manage the 802.1X authentication endpoints (thus, the ones that will deal with EAP-SH). To explore EAP-SH, users may create Wi-Fi access profiles, just as they usually do with their home or work Wi-Fi networks, to enforce the interaction with the correct hotspots along time.

EAP-SH actually combines two kinds of authentications: an arbitrary authentication within a Captive Portal (usually password-based) and a certificatebased authentication, using asymmetric key pairs and public key certificates. This last method facilitates user authentications, as it enables users to authenticate many times during a configurable time span (the lifetime of certificates) without providing any input after a successful Captive Portal authentication.

For dealing with HTTP-based interactions with Captive Portals, EAP-SH creates a TLS (Transport Layer Security [34]) tunnel over EAP for transferring HTTP messages between a user browser and the Captive Portal's Web server. This tunnel allows the user browser to interact with a Captive Portal Web service before the user host having an IP address (the IP configuration will only take place after succeeding in the 802.1X authentication protocol).

We implemented a prototype of EAP-SH in two open-source Linux applications that implement the 802.1X EAP endpoints: wpa\_supplicant and freeRA-DIUS. Our prototype implementation was then successfully tested on a real setup with a very simple, password-based Captive Portal.

This paper is structured as follows. Section 2 presents the technical foundations of the 802.1X authentication. Section 3 presents the security issues raised by the lack of link security in hotspot networks controlled by a Captive Portal. Section 4 presents some related work. Section 5 presents our EAP protocol (EAP-SH) and discusses some alternative exploitation scenarios. Section 6 describes an implementation of EAP-SH and its experimentation with a very simple Captive Portal. Section 7 compares the performance of EAP-SH with similar solutions. Section 8 discusses the security of EAP-SH and compares it with the security-flawed Captive Portal solutions. Finally, Section 9 presents the conclusions and foresees future work.

# 2 Technical Foundations

The 802.11i standard [28] defines the foundations for most of the security mechanism used in 802.11 wireless networks. Other standards exists, such as 802.11w [29], which is also related with 802.11i, for complementing the security for 802.11 networks.

802.11i uses the 802.1X authentication architecture [30] for performing mutual authentication on the access of a mobile host to a wireless network. The 802.1X architecture comprises a Supplicant (the mobile host), an Authenticator (an Access Point, AP) and an Authentication Server (AS), typically implemented by a RADIUS server [35]. This is commonly referred as an enterprise architecture, because it is more suitable for networks with a large amount of users. In some environments, usually referred as SOHO (Small Office, Home Office), the architecture can be simplified and the AS is not used; this is not our case.

The 802.1X enterprise authentication process has three phases, graphically displayed in Figure 1.

In the first phase, the Supplicant performs a useless network authentication (Open System Authentication) just for fulfilling a mandatory state-machine step inherited from WEP (Wired Equivalent Privacy), the 802.11i predecessor, and requests its association to the AP.

Then, we have the second phase, in which the Supplicant engages on a mutual authentication process with the AS. This process is not fixed; many authentica-

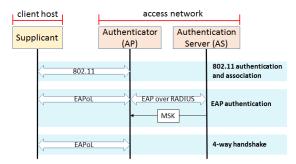


Figure 1: 802.1X authentication architecture: entities and phases. EAPoL stands for EAP over LAN and MSK stands for Master Session Key

tion protocols can be used. However, they are all encapsulated on EAP [1]. The reason for using the EAP encapsulation is to allow the Authenticator to recognize the messages exchanged in this phase, which need to be relayed back and forth between the Supplicant and the AS. There are many EAP authentication protocols [9]; among them, we have EAP-TLS and the one that we propose in this paper, EAP-SH.

EAP-TLS [41] is fundamentally the establishment of a TLS [34] session with a mutual authentication being performed with pairs of asymmetric keys and X.509 public key certificates [7]. EAP-SH is more complex, as it can be used to enroll a user in a network provider using a Captive Portal, to fetch a certificate for a Supplicant upon a proper authentication of its user with a Captive Portal, and then it may work as EAP-TLS with that certificate.

The outcome of all successful EAP authentications is a Master Session Key (MSK), which is shared between the Supplicant and the AS. The AS uploads this key to the Authenticator, which uses it to run the third 802.1X phase.

In the third phase, both the Supplicant and the Authenticator derive a PMK (Pairwise Master Key) from MSK and run the so-called four-way handshake. The purpose of this phase is to perform a mutual authentication between Supplicant and Authenticator using PMK and to derive a set of shorter-term traffic protection keys.

These traffic protection keys will subsequently be used to perform the 802.11i encryption and integrity control of the data frames exchanged between the Supplicant and the Authenticator. The 802.11i frame integrity control assures that attackers cannot inject false frames to any of the peers, Supplicant of Authenticator, on behalf of the other. Moreover, neither can an attacker replay past frames. Furthermore, the traffic protection keys will also protect management frames, namely 802.11 authentication and association frames, according with the 802.11w standard.

# 3 Captive Portals' security issues

The list below resumes all the security problems raised by the lack of link-layer security caused by the current exploitation of hotspots with Captive Portals:

- Clients can abuse the network through tunnels [33] over protocols that are always allowed, such as DNS [27].
- Clients' traffic is not encrypted at the link layer, and therefore can be captured in clear text by radio link eavesdroppers. While some traffic is already encrypted at the application layer, this is not the case for many Internet protocols;
- Traffic to and from clients does not have any source authentication or integrity control, and therefore MitM and impersonation attacks can be performed. An example of such attacks are session hijacking or freeloading [48]. Session hijacking allows an attacker to take control of a session that is being held by a client host with some other Internet host, while freeloading allows an attacker to explore network resources on behalf of a client host (without its knowledge);
- Clients and hosts, together, can be fooled by rogue hotspot APs, which can interfere with the clients' activities (e.g. by doing a DNS poisoning attack [2] or browser history stealing [8]);

The problems listed above are just an example of what can happen when one uses a hotspot without link-layer security. Without such security, both network clients and the network itself are open to traffic inspection and injection. This is a very significant security thread, which currently has no solution, not even with the mechanisms proposed in WPA3 (see Section 4).

# 4 Related Work

To the best of our knowledge, there are no previous proposals addressing the security problems created by the current paradigm for implementing Captive Portals as we did, i.e., by using the security standards developed for Wi-Fi, such as 802.1X, 802.11i and 802.11w. Nevertheless, we present some other solutions, addressing the issues raised by Captive Portals and with authentication of users accessing hotspots.

The Universal Access Method (UAM [17]) is a particular implementation of the Captive Portal paradigm, providing authentication through a Web browser. With this solution, the user requests a Web site and the destination IP address of that packet is shifted to an UAM handler. The UAM handler redirects the user to the UAM portal (Captive Portal), presenting a form that the user submits. The UAM handler then contacts a RADIUS server to authenticate the user and signals the beginning of the session. Captive Portals are ordinarily called upon clients' HTTP requests, using an HTTP redirection. A new HTTP status code 511 [26] was created to avoid confusions created by HTTP redirections implemented with other status codes that were being used to redirect HTTP clients (especially non-browser clients) to Captive Portals. This solution does not solve any of the security problems created by the Captive Portals paradigm, only helps to mitigate misinterpretations that can arise from the redirection performed by hotspot APs to force client machines to be authenticated prior to have access to the network.

Xia and Brustoloni [48] presented a solution for dealing with two security vulnerabilities created by Captive Portals: session hijacking and freeloading. Session hijacking is tackled with automatic reauthentications performed by the client host (more precisely, by its browser), which an attacker cannot do. Freeloading is tackled by following sequence numbers in frames and detecting two or more trend lines. However, the net result of both detection mechanisms is the disconnection of the victim client host from the network. Our solution simply does not allow session hijacking or freeloading to take place, because it enables the communication between clients and APs to be properly protected with 802.11i [28].

Godber and Dasgupta proposed an architecture based on a security gateway to implement an IPSec [13] tunnel with the clients' hosts upon a hotspot-based authentication [15]. This solution solves all security issues but introduces a performance bottleneck on the security gateway, while our solution uses the 802.11i [28] protection, which distributes the workload of wireless traffic protection by client hosts and APs.

Wi-Fi hotspots are open for public access, and for that reason they are not appropriate for exchanging authentication credentials between the clients and the AP. Some authors proposed that this could be solved by deploying a custom developed key establishment solution between a client host and an AP using a hierarchical identity-based cryptography set of methods [5]. As with other identity-based methods [40], an entity public key is derivable from a known attribute of the entity (e.g. an email address). The corresponding private key is generated by a third party, called the Private Key Generator (PKG), based on the entity's identity. However, this requires the setup of a secure channel between the entity and the PKG through which it can send the private key, which is a major disadvantage for scenarios requiring ad hoc contacts. The MAC address also serves as an identity (i.e., to generate a public/private key pair), with the drawback of involving all interface manufacturers (thus, raises scalability issues), and is not retro-compatible (network interfaces need to have a private key installed). Finally, it raises privacy issues, as the MAC address cannot be modified for preventing users' devices from being easily traced.

Hotspot 2.0, also called HS2 or Wi-Fi Certified Passpoint [3], is a standard for public access Wi-Fi. It is based on 802.11u [31] and features seamless roaming among wireless networks, as well as between Wi-Fi and cellular networks, increased bandwidth, and services-on-demand to end-users. This means that when a subscriber's device is in range of at least one Wi-Fi network, the device automatically connects to it and network discovery, registration, provisioning and access processes are automated. It uses an OSU (Online Sign Up) AP and OSU server to register future user authentication credentials (asymmetric key pair and certified public key), which will then be used in Production APs to authenticate the client with EAP-TLS [41]. This solution is somewhat similar to ours but it abolishes Captive Portals (while we keep them) and it requires APs to be modified (while we do not).

Apple's Captive Network Assistant (CNA) is a user agent (a limited browser) that automatically pops up and interacts with a Captive Portal when an Apple host connects to an open Wi-Fi network of a hotspot, instead of waiting for a browser request. The hotspot detection is based on Apple operating systems fetching a standard file from Apple servers, which is not served because of the redirection to the Captive Portal [23]. A similar solution is used by other operation systems, such as Microsoft Windows (since their Vista version). Similar assistants exist for other operating systems (e.g. Android), but not all assistants support all hotspots (since there is not standard approach for implementing them).

Another alternative to notify network client hosts of the necessity to connect to a Captive Portal is to provide its URI (Uniform Resource Identifier) within an optional field of an IPv4 DHCP (Dynamic Host Configuration Protocol) lease offer or as an extension of an IPv6 Router Advertisement message [19]. This enables clients to trigger an interaction with the network's Captive Portal upon the network configuration phase, instead of waiting for HTTP-based interactions initiated by the client user. This functionality, however, has no security benefits.

The Wireless Internet Service Provider roaming (WISPr [43, 42]) is a protocol chartered by the Wi-Fi Alliance where users are authenticated using UAM. WISPr authentication is done by smart-clients (small Web browsers) which use SSL/XML messaging to seamlessly login to hotspots without the need for users to interact with the Captive Portal. WISPr authentication allows a user to roam between wireless Internet Service Providers (ISPs), even if the hotspot pertains to one ISP for which the user may not have an account. For example, if a user that has an account with ISP X attempts to roam to a hotspot of ISP Y, the latter forwards the user's credentials to X's AAA (Authentication, Authorization and Accounting) server for authentication. Once ISP X authenticates the user, it is automatically authenticated in ISP Y, as per their service agreements. WISPr facilitates the sharing of hotspots among network providers, but does not solve any of the security issues previously presented.

WilmaGate [4] is a system for managing a single hotspots access network with several authenticators (where subscribers are registered). It does not solve any of the security issues previously referred.

In [21] the authors addressed the problem of getting credentials for users, as well as the hotspot public key certificate, using an NFC (Near Field Communication [44]) side-channel. These credentials can then be explored to perform an ordinary 802.1X authentication and set up a secure communication channel using the 802.11i security mechanisms. The drawback of this approach is that users need to have close-range contact with an NFC device to download the credentials. This approach could be used to complement our solution for providing

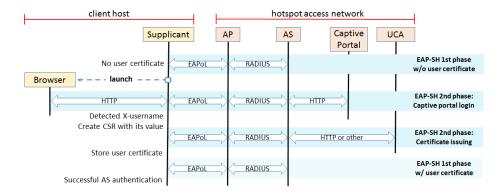


Figure 2: EAP-SH sequence of operations for authenticating a user on client host with a Captive Portal within a hotspot access network. The arrows represent one or more messages and show the protocol used in each interaction. The EAPoL (EAP over LAN) traffic is, in this case, EAP-SH traffic.

users with trustworthy self-certified certificates used by hotspots.

Recently was unveiled WPA3 (Wi-Fi Protected Access 3), an evolution of Wi-Fi security standards. Among the new features included in WPA3 there is an Enhanced Open [24] certification, based on Opportunistic Wireless Encryption (OWE [16]). OWE provides encryption in the wireless medium but no authentication, thus it cannot tackle active attacks by rogue APs [16, Section 7]. Furthermore, it does not facilitates the actual authentication with Captive Portals in any way.

# 5 EAP-SH: Extensible Authentication Protocol for Secure Hotspots

This section describes our proposal, EAP-SH, which brings together the 802.1X architecture with the Captive Portal paradigm. EAP-SH allows a client host (Supplicant) to be redirected to a Captive Portal through EAP, during which it has no granted IP access to the network. Therefore, no IP-based covert channels can be created before a successful user authentication (e.g. DNS tunneling). Furthermore, by embedding the access to a Captive Portal within EAP, and within the authentication and authorization processes used in 802.1X, we can benefit from the key derivation process of 802.1X, which enables the protection of the communications between a Supplicant and an AP with 802.111 protocols upon a successful mutual authentication. Finally, this EAP method was designed to allow a transparent user authentication using previously cached credentials, instead of relying all the time in a Captive Portal authentication.

### 5.1 Protocol overview

Besides the usual entities considered in the 802.1X architecture (Supplicant, Authenticator and AS), we propose three more (see Figure 2): a browser, a Captive Portal (a Web server) and a Users' Certification Authority (UCA).

The browser will run in the same machine of the Supplicant and will support the interaction with the Captive Portal (within a secure session established between the Supplicant and the AS). Note, however, that the browser will not establish a direct TCP connection with the Captive Portal, but with the Supplicant instead. The Captive Portal will receive HTTP messages from an AS, on behalf of a Supplicant, and will respond only to it. Finally, the UCA is responsible for issuing X.509 certificates for users upon a successful authentication on the Captive Portal. Those certificates are accepted for user authentication in the AS, and can be cached.

We assumed that the AS and the Captive Portal share a database with user profiles and accounting information. Regarding our protocol, the structure of such database is irrelevant.

Concerning the information shared between the ordinary 802.1X entities and the new ones, we only need the AS to know the UCA certificate (to get its public key), in order to validate certificates provided by users' Supplicants.

EAP-SH has two phases, similarly to other EAP methods [9], such as PEAP [32] and EAP-TTLS [41]. Those phases, for which high-level protocol flows are presented in Figure 2, are as follows.

In the 1st phase, there is an attempt to authenticate both Supplicant and the AS with X.509 public key certificates. The authentication of the AS cannot fail, while for the Supplicant this can happen. If the mutual authentication succeeds, EAP-SH terminates successfully.

If the Supplicant authentication could not be performed, the 2nd phase takes place, where the user is called to perform an HTTP-based authentication with a Captive Portal. The involved HTTP interaction is relayed by the Supplicant and the AS, under the protection a TLS secure session established during phase 1. Upon a successful authentication by the Captive Portal, the Supplicant creates a Certificate Signing Requests (CSR) and sends it to the UCA, in a communication relayed by the AS. Then, the UCA creates a user X.509 certificate and sends it to the Supplicant, again through the AS. Finally, the Supplicant resumes the protocol from the beginning, in order to perform a new mutual authentication with X.509 certificates.

For a user, the whole process involving client-side asymmetric credentials, which are obtained in phase 2 and used in phase 1, is completely transparent. Users are only called to interact in authentication processes when they have to interact with the Captive Portal, during the 2nd phase of EAP-SH. Thus, we keep the Captive Portal paradigm of user registration and we allow users to authenticate themselves with the well-known username plus password set of credentials, but we transparently simplify the users' authentication tasks by using the temporary asymmetric credentials.

Moreover, users are able to have multiple, simultaneous sessions with sepa-

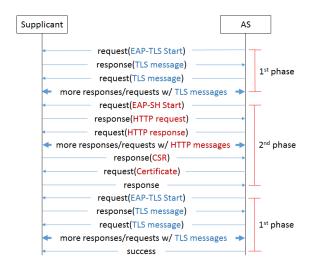


Figure 3: EAP-SH flow of messages between the Supplicant and the AS.

rate authentication data, which can be revoked independently.

### 5.2 EAP message flows of EAP-SH

An EAP authentication is a request-response protocol, where requests require the consequent reception of a response. Within 802.1X, the initiator of a requestresponse dialog is always the AS. The request-response dialog terminates with either an EAP success or failure message (both without payload and unacknowledged).

The 1st phase, or TLS phase, consists on the establishment of a TLS session between the Supplicant and the AS within a EAP-TLS protocol, which defines a mutual authentication of the Supplicant and the AS with asymmetric key pairs and public key X.509 certificates (see Figure 3). However, in EAP-SH the Supplicant authentication in this phase is optional, and decided by the Supplicant, while in EAP-TLS it is mandatory. When the Supplicant certificate is invalid or non-existent, this phase continues nevertheless, until completing the setup of the TLS session, and the authentication proceeds to a 2nd phase, which runs over that secure session.

Therefore, this phase terminates with one of two EAP messages:

- EAP success: this means that the user was properly authenticated during phase 1, and the EAP authentication, as far as the AS is concerned, is finished.
- EAP-SH Start: this means that EAP-SH must proceed to the 2nd phase.

The 2nd phase, or the Captive Portal phase, consists on the exchange of EAP-SH-specific messages encapsulating either HTTP messages, a CSR or a

X.509 certificate. This phase is successful if it terminates with the reception of a certificate by Supplicant, to be posteriorly used in the 1st phase of EAP-SH, together with the corresponding Supplicant's private key. Upon its termination, the AS initiates a new phase 1.

The success of the Captive Portal authentication is signaled to both the AS and the Supplicant with a custom HTTP header field (X-username) containing the user identity. Upon receiving it, the Supplicant generates a fresh asymmetric key pair, uses it to build a CSR [39] for that identity and sends it to the AS.

The so-called "X-" headers have been deprecated by RFC 6648 [37]. This is not a problem, on the contrary. Since they were deprecated, it is unlikely that our solution clashes with the use of a similar header field, which is an advantage. On the other hand, this header field is added by the AS and removed by the Supplicant, therefore it is never observed outside the EAP-SH.

When the Supplicant receives this certificate, it stores it and re-initiates the EAP-SH protocol, starting again from phase 1, which will (conceivably) authenticate the user with their asymmetric credentials, as in EAP-TLS.

Upon a successful mutual authentication of both Supplicant and AS at the end of phase 1 of EAP-SH, the MSK to be used by both Supplicant and AP to run the remainder of the 802.1X protocol is generated just like in EAP-TLS.

### 5.3 EAP messages' structure

EAP messages have a standard header structure [1], and a variable payload structure, depending on the specific EAP protocol being used. Therefore, we have defined our own payload for EAP-SH, which is as follows.

The EAP protocol does not support fragmentation of messages longer than 1020 bytes. Since with EAP-SH we need to transfer possibly longer contents between a Supplicant and an AS (e.g. certificates, Web pages, etc.), we need to handle their fragmentation on the EAP-SH level.

Both requests and responses may, in some cases (e.g. when fragmentation is used), serve as an acknowledgment of the reception of a specific fragment.

We use two payload structures, one for each phase. For phase 1 we did not need to modify the EAP-TLS payload structure, which we borrowed for our 2nd phase. For this, the fields of the EAP payload are the following (see Figure 4):

• Flags: 1-byte long set of bit flags. The L bit (length included) is set to indicate the presence of a message length field in the following bytes. This is used only on the first fragment of a fragmented message. The M bit (more fragments) is set to indicate if more fragments are to come; it is active on all fragments but the last. The H bit is set to indicate that the EAP-SH payload contains an HTTP request coming from the Supplicant; for HTTP responses, this bit is set to zero. The C bit is set when the Supplicant sends its CSR or when the AS sends the Supplicant's certificate for a future EAP-SH phase 1. Finally, the S bit (EAP-SH start) is set when the AS initiates the 2nd phase. Fragment acknowledgments have all of their flag bits set to zero.

- Message length: This is is a 4-byte field with the big endian representation of the total length of a EAP-SH message. This length is only present on the first fragment of a fragmented EAP-SH message.
- **Payload:** This field can contain either an HTTP message (request or response), a Supplicant's CSR or a Supplicant's certificate.

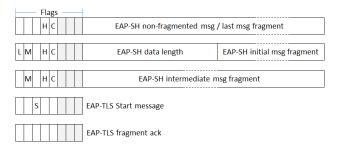


Figure 4: Structure of the EAP payload used for the 2nd phases of EAP-SH (right). This structure was borrowed from the EAP-TLS message structure. Although presented together, the H and C flags are not used simultaneously; only one of them, or none, are used at the time.

### 5.4 Privacy enhancement

EAP-TLS is known for having privacy problems, since it exposes the user identity in their certificate. Since the 1st phase of EAP-SH is almost identical to EAP-TLS, we also have that problem, which we attempted to solve.

However, privacy issues go beyond the exposure of identity labels. In fact, usually 802.11 network devices have a fixed MAC address, which means that, even concealing more human-related attributes, an attacker can still track devices as they move around. This was a key motivation for MAC address randomization in mobile devices, such as smartphones [20].

The EAP-TLS strategy for dealing with this privacy issue consists in repeating the protocol [41, § 2.1.4]: on a first step the Supplicant provides an empty certificate list in the Certificate Verify message, an AS configured for privacy accepts the response and continues with the setup of the secure session. Then, on a second step, the AS forces the Supplicant to run another TLS session setup, over the one previously created, but now with a proper certificate list in the Certificate Verify message. This strategy assumes that in the first step both peers agree on a ciphersuite supporting confidentiality.

We considered two alternative, and more lightweight, strategies.

One possibility is to negotiate a ciphersuite supporting confidentiality and use it to encrypt the certificate list provided in the TLS Certificate Verify message. A candidate key could be derived from the master secret, by increasing the length of key block that is used to derive all the required keys from the master key [41,  $\S$  2.3]. Note that the master key is derived from the pre-master key, which is provided to the AS by the Supplicant before sending the Certificate Verify message.

Another possibility is to use user pseudonyms in user certificates, which could be renewed for each new user certificate.

In the case that no other mechanisms are in place for preventing device tracking, such as the modification of the MAC address of the 802.11 network interface on each network association, the best strategy is the last one, the use of pseudonyms, since they do not add any extra information to the one already gathered using only the MAC address. Otherwise, the best strategies are the first two, since they both completely hide the details of the user certificate.

#### 5.5 Certificates, certification hierarchies and CSR's

The trust anchor of the whole EAP-SH process is the certificate of the AS of the hotspot provider. This certificate must be trusted by the Supplicants, directly or indirectly (by trusting some other certificate up on its certification chain, such as a certification root).

Note that Captive Portals do not need to have any certificate, because browsers do not interact directly with them. Browsers interact with the Supplicant, which interacts with the AS, which interacts with the Captive Portal. Thus, as long as the Supplicant trusts the AS certificate, the dialog between the browser and the right Captive Portal is assured. Also note that the entire dialog between the browser and the Captive Portal is open to inspection by the Supplicant and the AS, but encrypted while in transit between them. A second level of security between the browser and the Web server cannot be added as the AS partially processes HTTP messages.

Regarding the user certificates, these may be generated by some private Certification Authority (CA) known only by the AS, since only the AS needs to validate them. Thus, the UCA does not need to be inserted in some public certification hierarchy, it can certify itself, since for all that matters only the AS needs to trust on its certification public key.

The actual approach for implementing pseudonyms in users' certificates depends solely on the server side, thus they can be defined by the hotspot network providers. From our point of view, two strategies can be followed.

One strategy consists in having an extra column in the AS users' database with the pseudonyms. Pseudonyms may be random sequences generated by the AS upon a successful user authentication by the Captive Portal. In this case, all the AS has to do is to generate a pseudonym once it sees an X-username HTTP header attribute in a Captive Portal reply, insert the pseudonym in the user's database record and replace the value of the HTTP attribute by the pseudonym. Since the Supplicant generates a CSR with whatever comes in the X-username attribute, it will use the pseudonym transparently.

Another strategy consists in doing the same, but using a pseudonym computed by some encryption performed internally by the AS. In this case, the users' database does not need to have any extra column, since the AS can get the correct user identity by decrypting the user pseudonym. Different pseudonyms for the same user can be easily achieved by using some random data in the encryption process (e.g. encrypting with a secret key and a random Initialization Vector (IV) or encrypting with the AS public key with PKCS #1 or OAEP (Optimal Asymmetric Encryption Padding) paddings [22]).

For coping with any identity value provided by an AS, assuming that it is provided as a ASCII string, a Supplicant can simply use it as the Common Name in the Subject field of a CSR.

### 5.6 Dialog with the Captive Portal

The dialog between a user and a Captive Portal uses a browser, as usually. However, the browser is automatically launched by the Supplicant application only when necessary, i.e., when the authentication cannot be performed using asymmetric credentials. A simplified, or a more secure browser, can be used if necessary, and this is decided by the client or the Supplicant provider.

The browser connection is directed to a local URI, i.e., to the localhost Internet address and to a TCP port allocated by the Supplicant application. This port receives the HTTP traffic produced by the browser, which is then forwarded to the Captive Portal through the AS, which also establishes a TCP connection with the Captive Portal for that purpose. The reverse path of that HTTP traffic is treated similarly: the AS receives the responses from the Captive Portal, forwards them to the Supplicant, and this forwards them again to the browser. Therefore, the objects in the Web page (e.g. CSS, JavaScript, images) should be added by taking in consideration that resources are available to the browser at the localhost, and not at the Web server IP address.

The browser does not need to authenticate the Captive Portal, as in other solutions using Captive Portals. In fact, the network provider authentication is tackled in the establishment of the TLS tunnel, thereafter all the dialog between a browser and the Captive Portal is guaranteed to be performed with the correct entity because it goes through the TLS tunnel.

#### 5.6.1 Password management issues

Our transparent proxying between the user browser and the Captive Portal raises some issues related with the storage of login credentials by browsers' password managers. Today, and unless configured otherwise, browsers are extremely effective in helping users to memorize login credentials, usually spotted when HTML forms use an input field with the **password** type.

Browsers' password managers memorize login credentials associated to the URL portion that provides the service endpoint, i.e., its host name (or IP address) and TCP port. However, in our case we cannot guaranty that the Supplicant always uses the same TCP port to handle browsers' dialogues, unless a specific port could be allocated by IANA<sup>1</sup>. Furthermore, even if using the exact

<sup>&</sup>lt;sup>1</sup>Internet Assigned Numbers Authority, http://www.iana.org

same port, the constancy of the IP address (localhost) would merge credentials for different EAP-SH hotspots under the same memory record, in which case it may create problems if using the same username across different hotspot providers.

Concluding, it should not be easy to use browser's password managers to memorize users' credentials for accessing EAP-SH Captive Portals. The obvious option is, then, not to use such managers, and always input the login credentials in Captive Portals' interfaces. The non-memorization of credentials can be forced by Captive Portals, but this requires replacing simple and straightforward login HTML forms by JavaScript code capable of doing the same (as we did in our implementation, see Section 6.3). If such non-memorization is not forced, users must voluntarily reject the memorization of credentials each time they log in a Captive Portal, unless the browser provides some permanent disabling of that (which is only effective if the same local URL is presented to the browser).

### 5.7 Validation of the AS certificate

Usually certificates provided by servers, such as the AS, are validated by the Supplicant using certification hierarchies and certificate revocations. However, for checking certificate revocations one cannot resort to OCSP (Online Certificates Status Protocol [38]) servers, because the Supplicant at this point cannot use IP communications, and it is not practical to use Certificates Revocation Lists, because that would imply a pre-caching of all the required lists before performing a first connection with the AS.

The solution for this problem is to use the so-called OCSP stapling mechanism [11]. A TLS client may require, on its initial Hello message, the provisioning by the server of a signed OCSP message with the current revocation status of the server's certification chain. When the client appends to its Hello message a Certificate Status Request, the server sends, along with its certificate, a status field with an up-to-date OCSP response. This response allows the Supplicant to validate the server's certificate without having to initiate connections with OCSP servers.

# 6 Prototype Implementation

For evaluating the suitability of EAP-SH we implemented it using existing opensource applications for Linux systems. For the Supplicant we modified the wpa\_supplicant application; for the AS we modified a freeRADIUS server.

Regarding the UCA and the related certification services, we used a private PKI managed with calls to the openssl application. This application was also used by the Supplicant to create a CSR and by the AS (on behalf of a UCA) to issue a user certificate from a CSR.

Finally, the Captive Portal was implemented with a CherryPy<sup>2</sup> Web server.

<sup>&</sup>lt;sup>2</sup>http://cherrypy.org

This prototype was successfully used to perform consecutive logins with a Linux client host.

### 6.1 Supplicant

On Linux, the 802.1X Supplicant is played by a daemon that controls the 802.11 wireless networking, called wpa\_supplicant, which supports a wide variety of EAP methods <sup>3</sup>. Each EAP method is implemented as a separated module and all EAP methods use the same interface between the supplicant state machine and method-specific functions. Method registration is done through this interface. This allows new EAP methods to be added without modifying the core EAP state machine implementation.

Regarding this core implementation, all we had to do was to add a new EAP type number to the set of EAP type definitions. As of today, numbers 56 to 191 are unassigned  $^4$ , therefore we assigned to EAP-SH the type number 56.

As shown before, our EAP-SH incorporates an EAP-TLS phase, similarly to PEAP or EAP-TTLS [14]. For that reason, we adapted the wpa\_supplicant's PEAP module, which also uses TLS on a 1st stage, for implementing EAP-SH.

The TLS component of wpa\_supplicant is generic enough to be used alone or combined with other EAP methods. Namely, it supports client authentication (used by EAP-TLS) or is able to proceed without it. This was a perfect match for our EAP-SH.

#### 6.1.1 Configuration

The wpa\_supplicant configuration is given by a text file (usually wpa\_supplicant.conf) that lists all accepted networks and their security policies. It can include one or more network definition blocks, which include the entire necessary configuration for those networks.

For EAP-SH, the network block comprises a number of fields that contain critical information used when authenticating to a network, which are the following:

- ssid: Sequence of characters that uniquely identify a WLAN;
- key\_mgmt: Accepted authenticated key management protocol (WPA-EAP for EAP-SH);
- eap: EAP method used when authenticating to this network ({\EAPSH}, in our case);
- ca\_path: path of the directory containing CA certificates files to validate the network's AS certificate;

<sup>&</sup>lt;sup>3</sup>https://linux.die.net/man/8/wpa\_supplicant

<sup>&</sup>lt;sup>4</sup>http://www.iana.org/assignments/eap-numbers/eap-numbers.xhtml

- client\_cert and private\_key: Paths to the client's certificate file and corresponding private key file, respectively. The contents of these files, if valid, are used in the 1st phase of EAP-SH; every complete run of its 2nd phase updates their contents.
- private\_key\_password: The password used to protect the user private key used in the 1st phase of EAP-SH.
- browser\_command: The command to launch a browser to interact with the Captive Portal (through a local socket owned by wpa\_supplicant). We used the firefox -new-window %s command to launch the browser with a given URL, which would replace the parameter string %s.

Unlike for similar configurations, the user does not need to specify the ocsp field for requiring OCSP stapling, as EAP-SH does that by default.

#### 6.1.2 EAP-SH module on wpa\_supplicant

This module starts by instantiating a TLS tunnel, using or not the user authentication with asymmetric credentials. At the end of this step the AS sends an EAP message stating whether or not the user was authenticated during the setup of the TLS tunnel. This message has an empty payload; the information is solely coded in its S flag bit. If set, the wpa\_supplicant proceeds to the 2nd phase; otherwise, it terminates successfully.

For the 2nd phase, the wpa\_supplicant starts by allocating a socket and binding it to a random, local TCP endpoint (i.e., with an 127.X.X.X IP address and a port between 1025 and 65535). Then, it launches the user browser (as configured by the user) for accessing the URL constituted by the random TCP endpoint.

Upon this initial setup, the wpa\_supplicant enters the following processing cycle:

- 1. Read a full HTTP request from its TCP endpoint;
- 2. Transform the HTTP request into a TLS encrypted message and store it on one or more EAP-SH messages with the H bit set;
- 3. Send the EAP-SH message to the AS;
- 4. Receive EAP-SH messages with the H bit set from the tunnel, combine them until having a complete HTTP response, and send it to the TCP endpoint.
- 5. Search for an X-username field in the header of the HTTP response. If present, terminate this cycle and shutdown the TCP endpoint.

Once knowing the user pseudonym that should be used in their certificate, the wpa\_supplicant proceeds to create a new RSA key pair and a corresponding CSR. Then, the wpa\_supplicant encapsulates the CSR on a TLS message, stores

```
[ req ]
prompt=no
default_keyfile = "provided in the user's conf file"
output_password = "provided in the user's conf file"
default_bits = 1024
default_md = sha256
distinguished_name = DN
[ DN ]
CN = "pseudonym provided by the AS"
```

Figure 5: Configuration file provided to openssl to generate a user's CSR. Part of its contents are filled with data collected from the wpa\_supplicant configuration file

it on one or more EAP-SH messages with the C bit set and sends them to the AS.

Finally, the wpa\_supplicant waits for a final EAP-SH message from the AS, which must contain the user's public key certificate. It stores the certificate in a file with the path given by the configuration file and starts the whole process again, this time in the hope of terminating at the end of phase 1.

For this second round of EAP-SH, the TLS tunnel must be recreated from scratch, i.e., the previous TLS session cannot be reused. This is required to force the client authentication, which cannot take place when a TLS session is resumed.

#### 6.1.3 CSR generation

The CSR is generated with the openssl tool, using a configuration file created by wpa\_supplicant. The contents of that file are dynamic (i.e. the file does not need to pre-exist) and presented in Figure 5. The Subject's Common Name is filled with the identity provided by the AS, interpreted as an ASCII string. The key pair used in the CSR is always a new one, with 1024 bits.

### 6.2 RADIUS server

The authentication server was implemented by a modified RADIUS server. RA-DIUS [35] is a protocol that provides centralized Authentication, Authorization and Accounting management for users that connect and intend to use a network service. We decided to modify FreeRADIUS<sup>5</sup>, a popular open source RADIUS server, to implement the AS component of EAP-SH.

Similarly to wpa\_supplicant, adding EAP-SH to freeRADIUS implied creating a set of C files implementing the EAP interface methods (such as instantiate and process), and the protocol's logic. As for wpa\_supplicant, we adapted the freeRADIUS's PEAP modules to implement EAP-SH.

<sup>&</sup>lt;sup>5</sup>http://freeradius.org/

#### 6.2.1 HTTP handling and pseudonym generation

HTTP requests, once defragmented from EAP messages, are sent to the Captive Portal using a new socket connection. Then, the EAP-SH module waits for the HTTP response and, once complete, searches its header for the X-username field.

If present, it encrypts its value with AES-128 in CBC mode with PKCS #7 padding and a random IV. Then, the IV is concatenated with the resulting cryptogram, is authenticated with an HMAC [18] computed with SHA-1 [12] and the result is encoded in Base64, yielding the user's pseudonym:

c = AES-128-CBC(K, IV, identity || PKCS #7 padding)

 $pseudonym = Base64 (IV \parallel c \parallel HMAC (SHA-1, K, IV \parallel c))$ 

where K is the encryption and authorization key and  $\parallel$  denotes concatenation. The random IV assures that different pseudonyms will be generated for the same identity on different occasions.

The same key is used to encrypt the username and check for the integrity of a pseudonym. In our implementation, this key is volatile and generated each time the AS is launched. The consequence of its loss upon a server restart is that users need to fetch a new certificate, thus need to be authenticated by the Captive Portal.

The pseudonym is then used to replace the former value of the X-username field. Finally, the pseudonym is stored is a short term, volatile cache, for validating subsequent certification requests.

The pseudonym on a user certificate can be decrypted upon a successful 1st phase of EAP-SH, yielding the real username. This username can them be used for other operations, such as logging or authorization. We did not implement them in our prototype.

#### 6.2.2 CSR handling

When a CSR is received, its Subject's Common Name is fetched from it and checked against the pseudonyms cache. If present and still fresh (we used a 1-minute time window), the CSR is used to generate a new user's certificate.

To simplify the implementation for the proof of concept, the EAP-SH module also acts as a UCA. This actual certificate generation is performed by a shell script launched by the EAP-SH module, which uses the openssl command. All this command's parameters, such as the validity period of the users' certificates, are defined by this script. By using a script file, we are able to tune the parameters used in the certification process without having to change the freeRADIUS source code nor to add all the certification options to freeRADIUS configuration files.

### 6.2.3 Certificates and certification chains

For this prototype, we implemented a very simple PKI, formed by a root CA and an intermediate CA. The intermediate CA was used to issue the certificate

used by the EAP-SH module of RADIUS server and to issue client's certificates, upon reception of their CSR. To manage all the aspects of this PKI we also used openssl.

#### 6.2.4 EAP-SH module configuration

In order to integrate our protocol, the freeRADIUS EAP modules configuration file was changed accordingly. This file is parsed by the EAP-SH module upon its initialization and its contents are the following:

- certificate\_file: file with the AS certificate and certification chain;
- private\_key\_file: file with the AS private key;
- private\_key\_password: password to decrypt the private key file;
- ca\_file: server CA file, for validating Supplicants' certificates;
- user\_cerficate\_issuing\_script: shell script used to issue a user certificate;
- captive\_portal\_endpoint: the IP address and TCP port of the Captive Portal HTTP server.

### 6.3 Captive Portal

This server was implemented with a CherryPy Web server, implementing a very simple authentication page based on a username and a password. Its user database was implemented with SQLite<sup>6</sup>.

The login page uses an HTML form that was designed with the goal of preventing browsers from memorizing users' credentials. Empirically we found out that browsers are extremely effective in such memorization, which is triggered by the presence of an input field of type **password**.

Therefore, we replaced the **password** input type by **text** and used some extra JavaScript event handlers to hide the password, character by character, immediately after its input (see Figure 6). The original password characters are saved in a variable, which is copied (without any hashing) into a hidden form field when the latter is submitted. With this approach, we managed to disable the storage of user's passwords by the browsers' password manager while hiding the password typed from shoulder surfers.

The fact of not using a form input field of type **password** has another interesting side effect. Usually browsers warn users when they fill credential forms belonging to HTTP resources, because those forms will be exposed in the network on their submission. The way browsers detect the input of sensitive data, such as credentials, in forms is by the presence of fields of type **password**. Thus, because we did not use this field type, for the reasons presented above, we also

<sup>&</sup>lt;sup>6</sup>https://www.sqlite.org

avoid useless browser warnings (because, in our case, the browser session connects to a local port that forwards the HTTP traffic to a Captive Portal over a TLS tunnel; therefore, there is no risk).

If, in the future, browsers start imposing HTTPS-only access, there are two possible solutions: one is to disable (or not to implement at all) this feature for traffic that is internal to the machine; a second one is to provide an HTTPS endpoint on the Supplicant, using a certificate belonging to a certification chain used only internally. Naturally, the root of that certification chain would have to belong to the list of trusted roots used by local browsers.

```
<script>
var psw = ""
var star = "";
function hide() {
  var v = document.getElementById("psw").value;
  if (v.length < star.length) {
   psw = psw.substring(0, v.length - 1);
    star = star.substring(0, v.length - 1);
   else {
    star += "*";
    v = document.getElementById("psw").value;
   psw += v.slice(-1);
  document.getElementById("psw").value = star;
}
function unhide() {
  document.getElementById("hpsw").value = psw;
}
</script>
<form onsubmit=unhide() action="/login"
     method=post>
 <input type="hidden" name="hpsw" id="hpsw"
autocomplete=" off">
 Username<br>
  <input type="text" name="uname" required
          \verb+autocomplete="off"><\!\!br\!>
  Password<br>
 </form>
```

Figure 6: HTML login form, with JavaScript event handlers to save and hide the password as it is typed and to provide the saved password (without any post-processing, such as hashing) when the form is submitted (in its hidden input field "hpsw").

# 7 Performance evaluation

The performance of our solution depends on many technical aspects, many of them highly variable, such as the performance of the machines involved, the performance of the communications and the cost of the (asymmetric) cryptographic operations involved. In addition, it depends on the specific interaction with a Captive Portal and on pauses due to the required human-machine interaction. Therefore, we decided not to evaluate the performance of our solution in absolute terms, but rather to compare it theoretically with similar solutions.

The first time a user enters a hotspot network they need to run the complete protocol displayed on Figure 3. The first and the second phases, together, are similar to the actual authentication with a Captive Portal. In fact, Captive Portal authentications typically run over an HTTPS session (to protect the confidentiality of the credentials entered by users). Thus, our (initial) 1st phase is similar to the set-up of a TLS session within an HTTPS interaction, and our 2nd phase is similar to the HTTP interaction with a Captive Portal that runs within HTTPS. In both cases, the only differences are the EAP and RADIUS encapsulation displayed in Figure 2 (which add a small overhead on the exchanged data), and the generation and exchange of the CSR and user certificate at the end of the second phase.

For users that already have the asymmetric credentials fetched with the interactions previously referred, the authentications are equal to EAP-TLS (final first phase in Figure 3). Since this is intended to be the most frequent case, because the asymmetric credentials can be valid for some time (e.g. a day), EAP-SH will most of the time be as efficient as EAP-TLS.

Concluding, the only relevant overhead introduced by EAP-SH, when comparing with the actual authentication protocols used in Wi-Fi networks (including with Captive Portals), is the sporadic generation and exchange of a CSR and the corresponding certificate. Just to illustrate how small can this overhead be, both the generation of a CSR (with a new 1024-bit RSA key) and the generation of a certificate (signed by a 2048-bit RSA key) take around 100 milliseconds each in a Windows 10 host with an Intel core i7-8550U processor.

### 8 Security and Usability Analysis

With EAP-SH, the hotspot provider is authenticated with a certificate that needs to be pre-configured by the Supplicant. This means that, once such configuration has been done, the user does not need to pay attention to such action again (except if the certificate changes). This is not the case with the current Captive Portal authentication, where a user needs to pay attention to the effective security of every HTTPS session established with each Captive Portal.

The import of the hotspot certificate for the client hosts is, therefore, a critical task. Today this can be done in many different ways. For instance, the certificate may be downloaded from a secure Web page, using an existing network access, prior to use a hotspot (e.g. using a cellular interface). Alternatively, the certificate can be decoded from a QR code image displayed in a secure place (e.g. painted in the wall of a cybercafe), or downloaded from a distribution device using a wireless communication technology immune to MitM

attacks (e.g. NFC, as in [21]). In short, there are numerous secure ways to convey the hotspot certificate to its clients, but the discussion of their relative benefits is out of the scope of this paper. For what concerns us, this is not a complex problem to solve.

Although not previously referred, the EAP-SH paradigm can help users to identify when they are accessing a Captive Portal with it. In fact, the EAP-SH Supplicant software has access to the HTML contents provided by a Captive Portal, and can easily manipulate them in order to add to it some personal, visual content available only locally and customized by users. This way, a rogue Captive Portal Web page could not impersonate thz ones effective observed by each user for all EAP-SH based Captive Portals.

The EAP-SH approach extends the 802.1X paradigm. This means that it enables a secure interaction between the Supplicant and the AP upon a successful authentication between the Supplicant and the AS. This fact rules out some of the already referred attacks, such as session hijacking or freeloading [48] or DNS poisoning [2]. This is not possible with the current Captive Portal approach, where the wireless communication is never protected at the link layer.

The EAP-SH protects the hotspot provider from attacks deployed by nonauthenticated users. With the current Captive Portal paradigm, client hosts need to configure their network layer (get an IP address and a netmask), for which they need to run a DHCP negotiation. Many times, they are even allowed to perform DNS queries, which enables them to contact networks beyond the one of the hotspot provider (using, for instance, DNS tunnels [27]). All these possibilities represent a security risk, since such services can be abused and there is no way to identify the responsible person. On the contrary, with EAP-SH the client host does not have IP access to the network until successfully finishing its 802.1X authentication.

The CSR created by the Supplicant uses a user name (or pseudonym) that was given to the Supplicant and that is known by the AS. Therefore, a malicious Supplicant, once passed the Captive Portal authentication, cannot impersonate other users by using their pseudonym. This check is done when the AS receives the CSR, before forwarding it to the UCA.

# 9 Conclusion and Future Work

In this paper, we proposed a new EAP protocol, EAP-SH, which is able to merge two authentication paradigms: the one using Captive Portals and the one of 802.1X. The first is useful for enrolling new clients by a hotspot provider, and the second is able to provide security to the Wi-Fi link between a client host and the hotspot AP. The current Captive Portal paradigm is a hack that requires a special support by the APs and does not provide any security on the wireless link. On the contrary, EAP-SH, combined with 802.1X, requires the modification of the Supplicant and AS systems, but works with all existing APs that support the 802.1X enterprise mode, which is common nowadays. EAP-SH not only provides support for a Captive Portal authentication but it also enables client hosts to authenticate consecutively in the hotspot network without requiring users to provide authentication credentials (usually a username and password pair). This is achieved with the just in time issuing of client certificates, which may be cached by client hosts and used during the certificates' lifetime. The only drawback of our approach is the fact that users are not able to memorize their Captive Portal's credentials using the browsers' password management facilities, since there is no way to associate the right credentials to each hotspot provider. Nevertheless, the possibility of using the certificates to authenticate eases this problem, since the number of required Captive Portal authentications is reduced.

In terms of added security, EAP-SH clearly outperforms the current Captive Portal paradigm. Client hosts cannot use IP networking prior to complete their authentication, thus they are not able to use the network before completing their authentication. Hotspot providers can be authenticated with certificates associated with EAP-SH profiles, thus users are more protected from attacks by rogue hotspot providers. Finally, the wireless link between the client host and the hotspot AP is secured (encrypted and authenticated with 802.11i protocols) upon a successful authentication.

A prototype of EAP-SH was implemented in two Linux tools that implement the Supplicant and the AS of an 802.1X architecture: wpa\_supplicant and freeRADIUS. This prototype was successfully tested with a simple passwordbased Captive Portal, which was designed for avoiding clients' browsers to use their password manager to store users' credentials.

As future work, we can foresee several lines of action. A first one is to pursue the standardization of EAP-SH in the form of an IETF RFC. A second one is a closer integration of the Supplicant software with a browser for enabling the memorization of users' passwords by the browsers' password manager, a facility that is used by many users. Finally, a third one, also related with that closer integration, the presentation of a custom user interface provided by the Supplicant (e.g. a background image) to assure users that they are interacting with a given hotspot provider when they are called to provide their credentials to a Captive Portal.

# References

- B. Aboba, L. Blunk, J. Vollbrecht, J. Carlson, and H. Levkowetz. Extensible Authentication Protocol (EAP). RFC 3748 (Proposed Standard), June 2004.
- [2] S. Abu-Nimeh and S. Nair. Bypassing Security Toolbars and Phishing Filters via DNS Poisoning. In *IEEE Global Telecommunications Conf. (IEEE GLOBECOM 2008)*, New Orleans, LA, USA, November 2008.
- [3] Wi-Fi Alliance. Hotspot 2.0 (Release 2) Technical Specification, 2016.

- [4] M. Brunato and D. Severina. WilmaGate: A New Open Access Gateway for Hotspot Management. In Proc. of the 3rd ACM Int. Workshop on Wireless Mobile Applications and Services on WLAN Hotspots (WMASH '05), pages 56–64, Cologne, Germany, 2005.
- [5] J. Choi, SY. Chang, D. Ko, and YC. Hu. Secure MAC-layer protocol for captive portals in wireless hotspots. In 2011 IEEE Int. Conf. on Communications (ICC), pages 1–5. IEEE, 2011.
- [6] Cisco. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017-2022 White Paper, February 2019. http://www.cisco.com/c/en/us/solutions/collateral/serviceprovider/visual-networking-index-vni/mobile-white-paper-c11-520862.pdf.
- [7] D. Cooper, S. Santesson, S. Farrell, S. Boeyen, R. Housley, and W. Polk. Internet X.509 Public Key Infrastructure Certificate and Certificate Revocation List (CRL) Profile. RFC 5280 (Proposed Standard), May 2008. Updated by RFC 6818.
- [8] Adrian Dabrowski, Georg Merzdovnik, Nikolaus Kommenda, and Edgar Weippl. Browser history stealing with captive Wi-Fi portals. In *IEEE Security and Privacy Workshops (SPW 2016)*, pages 234–240, San Jose, CA, USA, May 2016.
- [9] R. Dantu, G. Clothier, and A. Atri. EAP methods for wireless networks. Computer Standards & Interfaces, 29(3):289–301, 2007.
- [10] John E. Duhn. Are public Wi-Fi hotspots a security risk? Security risks of using public Wi-Fi explained. Computerworld UK, August 2015. https://www.computerworlduk.com/security/are-public-wi-fi-hotspots-really-major-security-risk-3623447.
- [11] D. Eastlake 3rd. Transport Layer Security (TLS) Extensions: Extension Definitions. RFC 6066 (Proposed Standard), January 2011.
- [12] D. Eastlake 3rd and P. Jones. US Secure Hash Algorithm 1 (SHA1). RFC 3174 (Informational), September 2001. Updated by RFCs 4634, 6234.
- [13] S. Frankel and S. Krishnan. IP Security (IPsec) and Internet Key Exchange (IKE) Document Roadmap. RFC 6071 (Informational), February 2011.
- [14] P. Funk and S. Blake-Wilson. Extensible Authentication Protocol Tunneled Transport Layer Security Authenticated Protocol Version 0 (EAP-TTLSv0). RFC 5281 (Informational), August 2008.
- [15] A. Godber and P. Dasgupta. Secure Wireless Gateway. In Proc. 1st ACM Workshop on Wireless Security (Wise '02), pages 41–46, Atlanta, GA, USA, 2002.

- [16] D. Harkins and W. Kumari. Opportunistic Wireless Encryption. RFC 8110 (Informational), March 2017.
- [17] i Sprint. AccessMatrix UAM: common security platform for enterprise applications, 2000. http://www.i-sprint.com/brochure/uam\_en.pdf.
- [18] H. Krawczyk, M. Bellare, and R. Canetti. HMAC: Keyed-Hashing for Message Authentication. RFC 2104 (Informational), February 1997. Updated by RFC 6151.
- [19] W. Kumari, O. Gudmundsson, P. Ebersman, and S. Sheng. Captive-Portal Identification Using DHCP or Router Advertisements (RAs). RFC 7710 (Proposed Standard), December 2015.
- [20] J. Martin, T. Mayberry, C. Donahue, L. Foppe, L. Brown, C. Riggins, E. C Rye, and D. Brown. A Study of MAC Address Randomization in Mobile Devices and When it Fails. arXiv preprint arXiv:1703.02874, 2017.
- [21] A. Matos, D. Romão, and P. Trezentos. Secure hotspot authentication through a Near Field Communication side-channel. In *IEEE 8th Int. Conf. on Wireless and Mobile Computing, Networking and Communications (WiMob)*, pages 807–814, Oct 2012.
- [22] K. Moriarty, B. Kaliski, J. Jonsson, and A. Rusch. PKCS #1: RSA Cryptography Specifications Version 2.2. RFC 8017 (Informational), November 2016.
- [23] Aruba Networks. Apple Captive Network Assistant Bypass with Amigopod, Version 1.0, 2012. https://www.arubanetworks.com/vrd/ACNAAppNote/ wwhelp/wwhimpl/js/html/wwhelp.htm.
- [24] Aruba Networks. WPA3 and Enhanced Open: Next generation Wi-Fi security. White Paper, 2018. https://www.arubanetworks.com/assets/ wp/WP\_WPA3-Enhanced-Open.pdf.
- [25] Nomadix. Captive portal and the new security paradigm: Options for handling redirection problems caused by certificate mismatches, 2013. https://www.anixter.com/content/dam/Suppliers/nomadix/ SSL\_Redirection.pdf.
- [26] M. Nottingham and R. Fielding. Additional HTTP Status Codes. RFC 6585 (Proposed Standard), April 2012.
- [27] L. Nussbaum, P. Neyron, and O. Richard. On robust covert channels inside DNS. *Emerging Challenges for Security, Privacy and Trust*, pages 51–62, 2009.
- [28] LAN/MAN Standards Committee of the IEEE Computer Society. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 6: Medium Access Control (MAC) Security Enhancements. IEEE Std 802.11i, July 2004.

- [29] LAN/MAN Standards Committee of the IEEE Computer Society. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 4: Protected management Frames. IEEE Std 802.11w, July 2009.
- [30] LAN/MAN Standards Committee of the IEEE Computer Society. IEEE Standard for Local and Metropolitan Area Networks: Port-Based Network Access Control. IEEE Std 802.1X-2010, February 2010.
- [31] LAN/MAN Standards Committee of the IEEE Computer Society. Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 9: Interworking with External Networks. IEEE Std 802.11u, February 2011.
- [32] A. Palekar, D. Simon, J. Salowey, H. Zhou, G. Zorn, and S. Josefsson. Protected EAP Protocol (PEAP) Version 2. Internet draft draft-josefssonpppext-eap-tls-eap-10, October 2004. https://tools.ietf.org/html/ draft-josefsson-pppext-eap-tls-eap-10.
- [33] Matt Prytuluk. Two New Security Categories: DNS tunneling VPN and Potentially Harmful. Cisco Umbrella, November 2017. https://support. umbrella.com/hc/en-us/articles/115001077988-Two-New-Security-Categories-DNS-tunneling-VPN-and-Potentially-Harmful.
- [34] E. Rescorla. The Transport Layer Security (TLS) Protocol Version 1.3. RFC 8446 (Proposed Standard), August 2018.
- [35] C. Rigney, S. Willens, A. Rubens, and W. Simpson. Remote Authentication Dial In User Service (RADIUS). RFC 2865 (Draft Standard), June 2000.
- [36] Diego Rivera. Are captive portals a security challenge? Intraway, May 2017. https://thinkincredible.intraway.com/blog-post/captiveportals-security-challenge.
- [37] P. Saint-Andre, D. Crocker, and M. Nottingham. Deprecating the "X-" Prefix and Similar Constructs in Application Protocols. RFC 6648 (Best Current Practice), June 2012.
- [38] S. Santesson, M. Myers, R. Ankney, A. Malpani, S. Galperin, and C. Adams. X.509 Internet Public Key Infrastructure Online Certificate Status Protocol - OCSP. RFC 6960 (Proposed Standard), June 2013.
- [39] J. Schaad. Internet X.509 Public Key Infrastructure Certificate Request Message Format (CRMF). RFC 4211 (Proposed Standard), September 2005.
- [40] A. Shamir. Identity-based cryptosystems and signature schemes. In Advances in Cryptology: CRYPTO '84 (LNCS 196), volume 84, pages 47–53. Springer, 1984.

- [41] D. Simon, B. Aboba, and R. Hurst. The EAP-TLS Authentication Protocol. RFC 5216 (Proposed Standard), March 2008.
- [42] TK. Tan and B. Bing. Wi-Fi Hotspots. The World Wide Wi-Fi: Technological Trends and Business Strategies, pages 75–95, 2003.
- [43] Richard Thurston. WISPr 2.0 boosts roaming between 3G and Wi-Fi. ZD-Net, June 2010. http://www.zdnet.com/article/wispr-2-0-boostsroaming-between-3g-and-wi-fi.
- [44] R. Want. Near field communication. *IEEE Pervasive Computing*, 10(3):4– 7, July 2011.
- [45] WeLiveSecurity. 10 steps to staying secure on public Wi-Fi, September 2015. https://www.welivesecurity.com/2015/09/02/10-stepsstaying-secure-public-wi-fi.
- [46] wififreak. Captive Portals. IETF HTTP Working Group Wiki, February 2016. https://github.com/httpwg/wiki/Wiki/Captive-Portals.
- [47] WirelessPhreak. Captive Portal and HSTS difficulties, May 2017. https://www.wirelessphreak.com/2017/05/captive-portal-andhsts-issues.html.
- [48] H. Xia and J. Brustoloni. Detecting and Blocking Unauthorized Access in Wi-Fi Networks. In Proc. of the Third IFIP-TC6 Int. Conf. on Research in Networking (Networking 2004), Athens, Greece, May 2004.