

Who Is Peeping at Your Passwords at Starbucks? – To Catch an Evil Twin Access Point

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Abstract—In this paper, we consider the problem of “evil twin” attacks in wireless local area networks (WLANs). An evil twin is essentially a phishing (rogue) Wi-Fi access point (AP) that looks like a legitimate one (with the same SSID name). It is set up by an adversary, who can eavesdrop on wireless communications of users’ Internet access. Existing evil twin detection solutions are mostly for wireless network administrators to verify whether a given AP is in an authorized list or not, instead of for a wireless client to detect whether a given AP is authentic or evil. Such administrator-side solutions are limited, expensive, and not available for many scenarios. For example, for traveling users who use wireless networks at airports, hotels, or cafes, they need to protect themselves from evil twin attacks (instead of relying on those wireless network providers, which typically may not provide strong security monitoring/management service). Thus, a lightweight and effective solution for these users is highly desired. In this work, we propose a novel user-side evil twin detection technique that outperforms traditional administrator-side detection methods in several aspects. Unlike previous approaches, our technique does not need a known authorized AP/host list, thus it is suitable for users to identify and avoid evil twins. Our technique does not strictly rely on training data of target wireless networks, nor depend on the types of wireless networks. We propose to exploit fundamental communication structures and properties of such evil twin attacks in wireless networks and to design new active, statistical and anomaly detection algorithms. Our preliminary evaluation in real-world widely deployed 802.11b and 802.11g wireless networks shows very promising results. We can identify evil twins with a very high detection rate while keeping a very low false positive rate.

I. INTRODUCTION

Wireless networks are becoming extremely popular with the rapid advance of wireless LAN techniques and the wide deployment of Wi-Fi equipment. Users can easily access the Internet wirelessly when they are at home, at work, or even traveling. However, there is an emerging threat that can severely compromise the security of wireless users – evil twin attacks. An evil twin in a wireless LAN is essentially a phishing (rogue) Wi-Fi access point (AP) that looks like a legitimate one (with the same SSID name), but actually has been set up by an adversary, who can eavesdrop on wireless communications of users’ Internet access.

An evil twin attack is easy to launch. First, by using specific readily-available software [4], an attacker can simply configure a laptop to be an access point in a wireless network. Then, the attacker can figure out the SSID and the radio frequency that the legitimate AP is using. Finally, the attacker can phish victim users, by deploying her own access point with the same SSID as the legitimate AP is utilizing. An evil twin

attack is easy to be successful. The attacker typically positions (physically) the “evil twin” closer to the victim users than a trusted AP (good twin) so that the evil twin has the strongest signal within the range of the victim machine. Many users will be tempted by the higher signal strength if they want to manually choose an AP. In many cases, the end-users’ computers will automatically choose the evil twin connection when there are multiple APs associated with the same SSID. This is because when the wireless card senses local available wireless networks, most operating systems will choose the one with the best Received Signal Strength Indication (RSSI) [2] for each unique SSID based on the belief that all APs that have the same SSID and different frequency channels are organized under the same centralized server. Thus, such an evil twin attack is also very stealthy. In addition, these attacks are hard to trace because they can be launched and shut off suddenly or randomly, and last only for a short time after the attacker achieves her goal.

An attacker typically launches evil twin attacks near free hotspots, such as airports, cafes, hotels and libraries. Through setting up the evil twin, the attack can intercept sensitive data such as passwords or credit card information by snooping at the communication links, or launching man-in-the-middle attacks. The attacker can also manipulate DNS servers/communications, control the routing, and launch more severe phishing or other attacks. In short, evil twin is a serious threat to wireless LAN security.

All existing evil twin detection solutions can be classified into two categories. The first approach [12], [5], [8], [10], [7], [6], [9], [1], [3], [13] monitors Radio Frequency (RF) airwaves and/or additional information gathered at router/switches and then compares with a known authorized list. The second approach [33], [35], [34], [24], [32], [14], [31] monitors traffic at wired side (a traffic aggregation point such as gateway) and determines if a machine uses wired or wireless connections. Such information is further compared with an authorization list to detect if the associated AP is a rogue one. These approaches are limited because they all require the knowledge of an authorization list of APs and/or users/hosts. We consider these solutions to be network administrator oriented, as opposed to user oriented. That is, they are designed for a wireless network administrator to perform authorization and access control policies for wireless APs/users. However, for a client user, it is of particular importance to be able to identify evil twins. For example, traveling users who use wireless

networks at airports, hotels, or cafes need to protect themselves from evil twin attacks (instead of relying on those wireless network providers, which typically may not provide strong security monitoring/management service). Thus, a lightweight and effective solution for these client users is highly desired but is currently missing.

In this paper, we propose a novel user-side evil twin detection technique which has the following advantages compared to a traditional administrator-side solution: (i) Our technique does not require a known authorized AP/user list; (ii) An end user can be warned of an evil twin immediately to prevent being exposed to the attacker, even when the attack may last for a short time and a typical administrator-side solution may not help that much; (iii) From the user side, the parameters in a detection system can be customized according to local environment which may lead to a more accurate result; (iv) The user-side detection is resource-saving. The system can be activated only once when the users are trying to connect a new wireless AP. In addition, there is no need to modify the network architecture or any client- or server-side applications.

Our technique exploits the fundamental communication structure and properties of an evil twin attack: an evil twin typically still requires the good twin for Internet access. That is, an evil twin sits in the middle of the victim host and the good twin to relay communications. Thus, the wireless hops for a user to access Internet are actually increased (from one to two). In contrast, although legitimate wireless providers may use wireless bridges to extend the coverage, they do not change the single hop physical layer wireless channel to users. Based on this observation, we design new, active, statistical and anomaly detection algorithms to detect evil twins by differentiating the wireless hops (one or two hops). In addition, we consider the effect of throughput variance due to wireless network saturation and different RSSI ranges. We propose two algorithms: one is named Trained Mean Matching (TMM), requiring training knowledge of one-hop and two-hop wireless channels; and the other one is named Hop Differentiating Technique (HDT), which does not rely on any training information or knowledge. We apply these algorithms in the forms of sequential probability ratio test (SPRT) [30].

In short, our paper makes the following contributions:

- We propose the first user-side evil twin detection solution, to the best of our knowledge. Our technique does not rely on “fingerprint” checking of suspect devices nor require a known authorized AP/host list. Thus, this solution is particularly attractive to traveling users.
- We propose to exploit the intrinsic communication structure and property of evil twin attacks. Furthermore, we propose two statistical anomaly detection algorithms for evil twin detection, TMM and HDT. In particular, our HDT improves TMM by removing the training requirement. HDT is resistant to the environment change such as network saturation and RSSI fluctuation.
- We implement our techniques in a prototype system, ET-Sniffer (Evil Twin sniffer). We have extensively evaluated

ETsniffer in several real-world wireless networks, including both 802.11b and 802.11g. Our evaluation results show that ETsniffer can detect an evil twin quickly and with high accuracy (a high detection rate and a low false positive rate).

II. RELATED WORK

Existing rogue AP detection solutions can be classified into two categories. The first approach monitors RF airwaves and/or additional information gathered at routers/switches and then compares with a known authorized list. For example, AirDefense [12], similar to several other studies [5], [8], [10], [7], [6], [9], [1], [3], [13], scans RF from the Intranet APs to locate suspicious ones, and then compares specific “fingerprints” of the RF with an authorized list to verify. Specifically, for the scanning part, some studies [9], [1], [3] rely on sensors instead of sniffers to scan the RF, and some studies such as [13] propose a method to turn existing desktop computers into wireless sniffers to improve the efficiency. For verification, these studies verify MAC addresses, SSID, and/or location information of the AP by using an authorized list. However, these studies still have the risk of falsely claiming a normal neighbor AP as a rogue AP with a high probability. To solve this problem, they need to further verify whether such a rogue AP is indeed in the internal network. For example, Beyah’s work [15] uses a verifier to send packets to the wireless side, if such packets are received by the internal sensor, the associated AP is internal and thus an Evil Twin.

The second approach of rogue AP detection, proposed in [33], [35], [34], [24], [32], [14], [31], detects evil twins by differentiating whether clients come from wireless networks or wired networks, relying on the differences in diverse network protocols. If a client comes from a wireless network while it is not authorized to do so (comparing with an authorized list), the AP attached to this host is considered as a rogue AP. Wei’s work [34] is one of the earliest studies. [32], [24], [14] use some statistical features of the traffic time ([14] relies on the entropy, [32] relies on the median and the entropy, and [24] relies on the mean) to make decisions. [33], [19] detect rogue AP by analyzing the TCP-ACK pairs in their mathematical model. [31] treats different ranges of a TCP connection separately. [22] relies on the RTT sent to hosts to distinguish WLAN, and it takes some traffic factors into consideration to increase the precision. [17], [28] rely on the frequent rate adaptation in the wireless network to distinguish it with wired networks. However, this line of work should solve the problem of falsely claiming an authorized wireless user who connects to Intranet with wireless networks. Thus, they may still need to further verify a wireless device is an authentic AP or not with some “fingerprint” from authorized lists. [20], [26] are two hybrid studies that provide the fingerprint comparisons in the integrated systems.

Our work, ETsniffer, is different from all previous (administrator-oriented) work, since we do not require the knowledge of an authorized AP/host list. This is the first user-side evil twin detection scheme, to the best of our knowledge.

III. PROBLEM STATEMENT

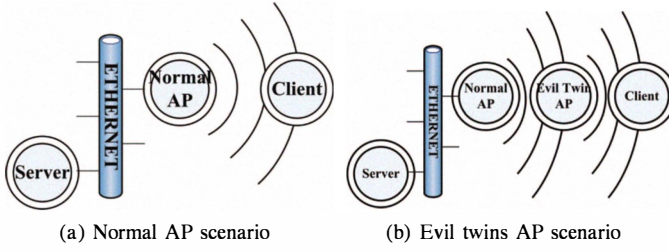


Fig. 1: Illustration of the target problem in this paper.

The goal of our work is to detect evil twin attacks in real time under real wireless network environments, i.e., we aim to detect whether there sits an evil twin AP between a normal AP and the user. Considering the normal AP scenario, depicted in Figure 1(a), a user communicates with a remote server through a normal AP using 802.11 WLAN; on the other hand, in the evil twin AP scenario, depicted in Figure 1(b), the victim client communicates with a remote server through an evil twin AP and a normal AP. In both two scenarios, the normal AP connects with the remote server through wired (Ethernet) networks. Obviously, compared with the normal AP scenario, the evil twin AP scenario has one more wireless hop. This observation gives us the intuition to detect evil twin attacks by differentiating one-hop and two-hop wireless channels.

To achieve the goal, we must answer the following three questions: (1) What statistics can be used to effectively distinguish one-hop and two-hop wireless channels on the user side? (2) Are there any dynamic factors in a real network environment that can affect such statistics? (3) How to design robust and efficient detection algorithms with the consideration of these influencing factors? Next, we provide a high-level description about our solutions to these questions and then explain details in Section IV and V.

For the first question, we choose Inter-packet Arrival Time (IAT) as the detection statistic. IAT is a time interval between two consecutive data packets sent from the same device (the remote server or the connected AP) to the client. In order to compute IAT more effectively and accurately, we adopt a new ACK-packet sending policy – an immediate-ACK policy, i.e., ETSniffer always immediately acknowledges every data packet received and the server sends next data packet only when receiving an acknowledge for the previous one.¹ It is different from traditional delayed-ACK policy in wireless networks, in which a receiver sends an ACK packet after receiving two continuous packets (or after the delayed-ACK timer is triggered) [21], [23]. Under the immediate-ACK policy, if ETSniffer receives two consecutive data packets P_1 and P_2 , and sends corresponding ACK packets A_1 and A_2 . Then, on the client side the packet sequence is in an order of $P_1A_1P_2A_2$. If we let T_{P_1} and T_{P_2} be the time when the

client receives P_1 and P_2 , respectively. Then the IAT can be computed as $T_{P_2} - T_{P_1}$.

For the second question, in a real wireless network environment, two main factors will affect IAT: Received Signal Strength Indication (RSSI) [2] and wireless network saturation. In wireless networks, RSSI fluctuates due to the multi-path and fading effects of the radio signal propagation. Since most wireless network cards have a transmission rate adaptation mechanism to adjust to different RSSI levels, the fluctuation of RSSI directly influences the practical available wireless bandwidth, causing the fluctuation of IAT. In addition, wireless network saturation is another influencing factor. When multiple devices synchronously attempt to send packets to the same AP, the medium access collisions emerge and spur the phenomenon of network saturation. This phenomenon stochastically increases the time for transmitting packets from a client to the AP. Specifically, according to CSMA/CD mechanism, the collisions set the exponential back-off time and account for an additional distributed inter-frame spacing (DIFS) [11], [29] time and a short inter-frame spacing (SIFS) [11], [29] time. Previous work such as [18], [16] shows that the throughput decreases with the increased number of the wireless clients, leading to larger IAT.

For the last question, we develop two new algorithms: Trained Mean Matching (TMM) and Hop Differentiating Technique (HDT). Both algorithms utilize wireless IAT network statistic, consider the influencing factors of RSSI and saturation, and employ Sequential Probability Ratio Test (SPRT) technique to make the final detection.

IV. SERVER IAT ANALYSIS

A. Theoretic Analysis of Server IAT

In this section, we show the theoretic analysis of Server IAT (IAT computed by the data packets sent from the server) and further demonstrate that Server IAT can be used to differentiate one-hop wireless channels and two-hop wireless channels, and thus it can be used to detect evil twin attacks.

First, we list used variables in our detection model and their settings (based on IEEE 802.11 standard [19]) in Table I. Since we consider both influencing factors (RSSI and network saturation), to better describe our model, we define the special wireless network environment with a perfect signal strength ($RSSI = 100\%$) and no wireless collisions as “an ideal network environment”. Let ΔA_S and $\tilde{\Delta A}_S$ be one Server IAT under the “real network environment” and the “ideal network environment”, respectively. B_W and B_E denote the bandwidth of wireless network and Ethernet, respectively. Let ρ denote the bandwidth occupancy of Ethernet. W_0 is the initial contention window size. T_{DIFS} is one DIFS time and T_{SIFS} is one SIFS time. T_{BFF} denotes the back-off time which follows a uniform distribution in terms of the contention window size. $L_{ACK(MAC)}$ and $L_{ACK(TCP)}$ are the size of an ACK-packet in the MAC layer and in the TCP layer, respectively. L_P denotes the size of one data packet that the client receives and $L_{\bar{P}}$ is the average packet size on the Internet, which is usually between 300 and 400 bytes [27].

¹Note that this is not a global policy. It only affects the specific probing sessions initialized by ETSniffer for detection. We discuss our implementation to enforce such policy in Section VI-A.

TABLE I: Variables and settings in our model

Protocol	802.11b	802.11g
B_W	11MBps	54MBps
B_E	100MBps	100MBps
W_0	32	16
T_{DIFS}	50 μ s	50 μ s
T_{SIFS}	10 μ s	10 μ s
$L_{ACK(MAC)}$	278Bytes	278Bytes
$L_{ACK(TCP)}$	338Bytes	338Bytes
L_P	402Bytes	402Bytes
$L_{\bar{P}}$	375Bytes	375Bytes

Then, based on IEEE 802.11 standard and our settings, we can show that the mean of ΔA_S is theoretically differentiable between the normal AP scenario and the evil twin scenario.

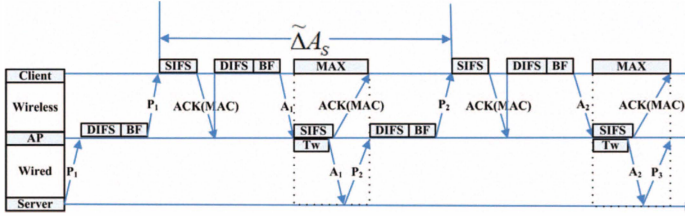


Fig. 2: Server IAT illustration in the normal AP scenario (one-hop wireless channel) in an ideal network environment.

Theorem 1. If we denote $E(\tilde{\Delta A}_S)_{one-hop}$ as the mean of Server IAT $\tilde{\Delta A}_S$ in a one-hop wireless channel, then in the normal AP scenario, we can get

$$E(\tilde{\Delta A}_S)_{one-hop} = 2T_{DIFS} + T_{SIFS} + 2E(T_{BF}) + \frac{L_{ACK(MAC)} + L_{ACK(TCP)} + L_P}{B_W} + E(T_{MAX}) \quad (1)$$

$$\text{Where, } T_{MAX} = \max \left(T_{SIFS} + \frac{L_{ACK(MAC)}}{B_W}, \frac{L_{ACK(TCP)} + L_P}{B_E} + T_{wait} \right) \text{ and } E(T_{wait}) = \frac{\rho}{2(1-\rho)} * \frac{L_{\bar{P}}}{B_E}$$

Proof: In the normal AP scenario, considering the procedure that the client receives two consecutive data packets P_1 and P_2 from the remote server and it sends ACK packets A_1 and A_2 correspondingly, we show the analysis in Figure 2. When A_1 arrives at the AP, the AP will wait for one T_{SIFS} time and then send an ACK-packet in the MAC layer back to the client. Since in the Ethernet, packets from other traffic may occupy the wired link, the AP will have to wait for some extra time to finish transmitting A_1 . We denote this extra time as T_{wait} . Commonly, the packets to the server will form an M/D/1 queue. Based on the M/D/1 queue theory, we can get

$$E(T_{wait}) = \frac{\rho}{2(1-\rho)} * \frac{L_{\bar{P}}}{B_E}$$

After receiving A_1 , the server will send P_2 to the AP. If the AP has not finished sending the ACK packet in the MAC layer to the client, the AP could not begin to send P_2 to the client. Thus, after A_1 arrives at the AP from the client, the AP will have to use T_{MAX} time to begin to prepare sending P_2 to the client, where

$$T_{MAX} = \max \left(T_{SIFS} + \frac{L_{ACK(MAC)}}{B_W}, \frac{L_{ACK(TCP)} + L_P}{B_E} + T_{wait} \right)$$

Thus, from Figure 2, we can get that

$$\tilde{\Delta A}_S = T_{P_2} - T_{P_1} \quad (2)$$

$$= T_{SIFS} + \frac{L_{ACK(MAC)}}{B_W} + T_{DIFS} + T_{BF} + \frac{L_{ACK(TCP)}}{B_W} + T_{MAX} + T_{DIFS} + T_{BF} + \frac{L_P}{B_W} \quad (3)$$

$$= 2T_{DIFS} + T_{SIFS} + 2T_{BF} + \frac{L_{ACK(MAC)} + L_{ACK(TCP)} + L_P}{B_W} + T_{MAX} \quad (4)$$

Thus,

$$E(\tilde{\Delta A}_S)_{one-hop} = 2T_{DIFS} + T_{SIFS} + 2E(T_{BF}) + \frac{L_{ACK(MAC)} + L_{ACK(TCP)} + L_P}{B_W} + E(T_{MAX}) \quad (5)$$

Theorem 2. If we denote $E(\tilde{\Delta A}_S)_{two-hop}$ as the mean of Server IAT $\tilde{\Delta A}_S$ in a two-hop wireless channel, then in the evil twin AP scenario, we can get

$$E(\tilde{\Delta A}_S)_{two-hop} = 4T_{DIFS} + T_{SIFS} + 4E(T_{BF}) + \frac{L_{ACK(MAC)} + 2L_{ACK(TCP)} + 2L_P}{B_W} + E(T_{MAX}) \quad (6)$$

$$\text{Where, } T_{MAX} = \max \left(T_{SIFS} + \frac{L_{ACK(MAC)}}{B_W}, \frac{L_{ACK(TCP)} + L_P}{B_E} + T_{wait} \right) \text{ and } E(T_{wait}) = \frac{\rho}{2(1-\rho)} * \frac{L_{\bar{P}}}{B_E}$$

Proof: (See our extended version [25] due to space limitation of this paper)

From theorem 1 and 2, if we let $E(\tilde{\Delta}_S)$ be the difference of $E(\tilde{\Delta A}_S)_{one-hop}$ and $E(\tilde{\Delta A}_S)_{two-hop}$, then

$$E(\tilde{\Delta}_S) = E(\tilde{\Delta A}_S)_{two-hop} - E(\tilde{\Delta A}_S)_{one-hop} = 2T_{DIFS} + 2E(T_{BF}) + \frac{L_{ACK(TCP)} + L_P}{B_W} \quad (7)$$

Under the real network environment, either the decrease of RSSI or the increment of wireless collisions can increase Server IAT, causing the distribution of Server IAT not so steady as that under the ideal network environment. However, the evil twin scenario has one more wireless hop leading to a larger probability of increasing Server IAT than that of the normal AP scenario. Therefore, if we let $E(\Delta A_S)_{one-hop}$ and $E(\Delta A_S)_{two-hop}$ as two means of ΔA_S in one-hop and two-hop wireless channels under the real network environment, we can get

$$E(\tilde{\Delta}_S) = E(\Delta A_S)_{two-hop} - E(\Delta A_S)_{one-hop} \approx E(\tilde{\Delta}_S) = 2T_{DIFS} + 2E(T_{BF}) + \frac{L_{ACK(TCP)} + L_P}{B_W} \quad (8)$$

We can see that the mean of ΔA_S in the evil twin AP scenario is larger than that in the normal AP scenario, thus this observation can be used to detect evil twin attacks.

B. Practical Validation of Server IAT

In this section we show our experimental results to validate whether Server IAT is an indeed suitable and effective statistic to differentiate one-hop and two-hop wireless channels.

To minimize data bias, for both one-hop and two-hop wireless situations, we build our datasets under real network environments at three different times. We compute Server IAT in one-hop and two-hop wireless channels by collecting the

packets under the conditions of RSSI = 100 and RSSI = 50. The result is shown in Figure 3. We can see that the distribution of Server IAT keeps stable when RSSI is 100%. The two means of IAT in one-hop and two-hop wireless channels are about 1,300ms and 3,300ms, respectively. The gap of these two means is obvious. Although when the signal strength decreases (e.g., RSSI at 50%), the distribution of Server IAT is not so stable as that when RSSI is 100, this gap can still be legibly observed.

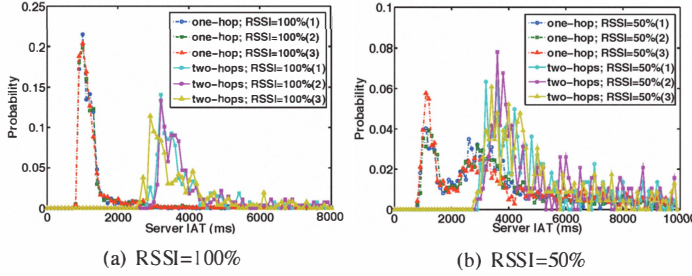


Fig. 3: IAT distribution in one- and two-hop wireless channels.

V. DETECTION ALGORITHM

Based on our theoretical analysis and practical validation in the previous section, we present two algorithms to detect evil twin attacks: Trained Mean Matching (TMM) and Hop Differentiating Technique (HDT). Both algorithms utilize Sequential Probability Ratio Test (SPRT) technique [30]. TMM algorithm requires knowing the distribution of Server IAT as a priori (trained) knowledge. However, HDT algorithm does not need such a requirement. Instead, it is directly based on theoretical analysis. Thus, it is more suitable for scenarios where the distribution of IAT is either unknown, instable, or unable to be (perfectly) trained.

A. Trained Mean Matching Algorithm

1) *TMM Algorithm Description*: We have demonstrated that the distributions of Server IAT in one-hop and two-hop wireless channels differ significantly. According to this observation, in this section, we develop a detection algorithm named Trained Mean Matching (TMM). Specifically, given a sequence of observed Server IATs, if the mean of these Server IATs has a higher likelihood of matching the trained mean of two-hop wireless channels, we conclude that the client uses two wireless network hops to communicate with the remote server indicating a likely evil twin attack, and vice versa.

In the training phase, we adopt a quadratic-mean technique to train a detection threshold. First, we collect Server IAT in both one-hop and two-hop wireless channels. Then, we compute the mean and the standard deviation of Server IAT collected in the one-hop (normal AP) scenario, denoted as $\mu_{1,NAP}$ and $\sigma_{1,NAP}$, respectively. Then, we filter out the Server IATs beyond the range $[\mu_{1,NAP} - \sigma_{1,NAP}, \mu_{1,NAP} + \sigma_{1,NAP}]$. Next, we derive the second mean using the residual Server IAT, denoted as $\mu_{2,NAP}$. Similarly, we can obtain the second mean of Server

IAT in the two-hop (evil twin AP) scenario, denoted as $\mu_{2,EAP}$. We compute the average of $\mu_{2,NAP}$ and $\mu_{2,EAP}$, as T_θ , set as the boundary to differ one-hop and two-hop Server IAT. In addition, in order to use SPRT technique, we obtain two probabilities of a Server IAT in these two scenarios exceeding the trained threshold, denoted as P_1 and P_2 , by computing the percentage of collected Server IATs deviating from T_θ in the normal and evil twin AP scenario, respectively.

In the detection phase, given a sequence of Server IAT observations, represented by $\{\delta\}_{i=1}^n$, we use a binary random variable γ_i to denote whether the i th observed Server IAT belongs to evil twin AP scenario or not. Specifically, if $\delta_i \geq T_\theta$, then $\gamma_i = 1$, indicating an estimated evil twin AP scenario; otherwise, $\gamma_i = 0$, indicating an estimated normal AP scenario. Thus, we get a sequence of $\{\gamma\}_{i=1}^n$. Let H_1 be the hypothesis that it belongs to an evil twin AP scenario and H_0 be the hypothesis that it belongs to a normal AP scenario. We denote $P(\gamma_i = 1|H_1) = \theta_1$ and $P(\gamma_i = 1|H_0) = \theta_0$. According to the training data, we can set $\theta_0 = P_1$ and $\theta_1 = P_2$. We can compute the log-likelihood ratio Λ_n with the assumption that the Server IAT observations are i.i.d. (independent and identically-distributed) as the following formula:

$$\begin{aligned} \Lambda_n &= \ln \frac{Pr(\gamma_1 \dots \gamma_n | H_1)}{Pr(\gamma_1 \dots \gamma_n | H_0)} = \ln \frac{\prod_{i=1}^n Pr(\gamma_i | H_1)}{\prod_{i=1}^n Pr(\gamma_i | H_0)} \\ &= \sum_{i=1}^n \ln \frac{Pr(\gamma_i | H_1)}{Pr(\gamma_i | H_0)} \end{aligned} \quad (9)$$

According to SPRT [30], we perform a threshold random walk to calculate the log-likelihood ratio. The walk starts from zero. If $\gamma_i = 1$, then it goes up with a length of $\ln(\theta_1) - \ln(\theta_0)$; if $\gamma_i = 0$, then it goes down with a length of $\ln(1 - \theta_1) - \ln(1 - \theta_0)$. We define every random walk as one decision round. Let us denote α and β as the user-chosen false positive rate and false negative rate, respectively. If the random walk reaches the upper boundary $B = \ln(1 - \beta) - \ln \alpha$, we report evil twin AP scenario; if it reaches the lower boundary $A = \ln \beta - \ln(1 - \alpha)$, we report normal AP scenario; otherwise, it is pending and we watch for the next decision round.

2) *Discussions of TMM Algorithm*: Based on the training technique, TMM algorithm affords an effective approach to detect evil twin attacks. However, in some cases, it is too time-consuming or impractical for a normal user to acquire a priori knowledge, particularly the training data for two-hop wireless channels. In addition, the trained knowledge in one wireless network is hardly directly applicable to another network. These limitations motivate us to design a new effective and practical non-training-based algorithm to detect evil twin attacks – Hop Differentiating Technique (HDT).

B. Hop Differentiating Technique

In HDT algorithm, instead of using the absolute value of IAT, we adopt another metric – the ratio of a Server IAT to an AP IAT. We define it as SAIR (Server-to-AP IAT Ratio). Next, we theoretically prove that it can be used to robustly detect evil twin attacks.

1) *Theoretic Analysis of SAIR*: Before illustrating our theoretical analysis of SAIR, we first make three reasonable assumptions:

- The wireless network environment does not change extremely dramatically, which implies a relatively steady RSSI and collision number at least during the period when we collect one pair of Server IAT and AP IAT to compute a SAIR.
- In the evil twin AP scenario, the RSSI and the situation of network saturation of the link between the victim client and the evil twin AP are not worse than that between the victim and the normal AP.
- The Ethernet is not under the situation of severe network congestion.

For the first assumption, since the time cost during collecting one pair of Server IAT and AP IAT is in seconds, it is reasonable to assume the wireless network environment does not change dramatically during such a short time interval. For the second one, since the attacker wants to successfully allure victim clients to connect with the evil twin AP, it is more likely for the attacker to provide a better RSSI and a smaller wireless collision probability. For the last one, if there is a severe network congestion in the Ethernet, few people would choose the normal AP to surf the Internet.

Next, we introduce some variables to better describe our model. Let ΔA_A be the AP IAT and α be the SAIR, under the real network environment. Let $\tilde{\Delta A}_A$ be the AP IAT and $\tilde{\alpha}$ be the SAIR under the ideal network environment. Then, we can get

$$\alpha = \frac{\Delta A_S}{\Delta A_A} \text{ and } \tilde{\alpha} = \frac{\tilde{\Delta A}_S}{\tilde{\Delta A}_A} \quad (10)$$

Then, based on IEEE 802.11 standard and our settings, we next prove that the mean of α is theoretically differentiable between the normal AP scenario and the evil twin AP scenario, and thus can be used to effectively detect the evil twin attacks. Similar to Theorem 1, we can get the mean of AP IAT as illustrated in Figure 4.

$$E(\tilde{\Delta A}_A)_{one-hop} = 2T_{DIFS} + 2T_{SIFS} + 2E(T_{BF}) + \frac{2L_{ACK(MAC)} + L_{ACK(TCP)} + L_P}{B_W} \quad (11)$$

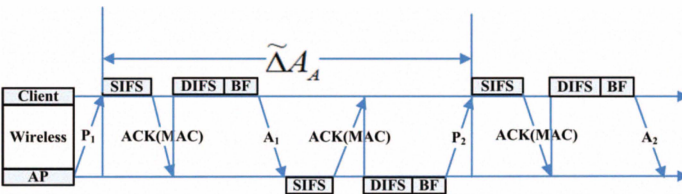


Fig. 4: AP IAT illustration in an ideal network environment.

We have the following two theorems that give us theoretic evidence on the effectiveness of this detection statistic.

Theorem 3. If we denote $E(\alpha_{one-hop})$ and $E(\tilde{\alpha}_{one-hop})$ as the mean of α and $\tilde{\alpha}$ in one-hop wireless channels, then we can get: for WLAN 802.11b, $E(\alpha_{one-hop}) \leq E(\tilde{\alpha}_{one-hop}) = 1.00$; for WLAN 802.11g, $E(\alpha_{one-hop}) \leq E(\tilde{\alpha}_{one-hop}) = 1.11$.

Proof: (See our extended version [25]) ■

Theorem 4. If we denote $E(\alpha_{two-hop})$ and $E(\tilde{\alpha}_{two-hop})$ as the mean of α and $\tilde{\alpha}$ in two-hop wireless channels, then we can get: for WLAN 802.11b, $E(\alpha_{two-hop}) \geq E(\tilde{\alpha}_{two-hop}) = 1.74$; for WLAN 802.11g, $E(\alpha_{two-hop}) \geq E(\tilde{\alpha}_{two-hop}) = 1.94$.

Proof: (See our extended version [25]) ■

From Theorem 3 and 4, we can see that the theoretical mean of α in evil twin AP scenario is significantly larger than that in the normal AP scenario, thus it can be used to detect evil twin attacks.

2) *HDT Algorithm Description*: In the previous section, we have proved that SAIRs in one-hop and two-hop wireless channels differ significantly. Even under the real network environment, we can still compute a theoretical SAIR bound to distinguish these two scenarios. According to this observation, in this section, we develop a non-training-based detection algorithm named Hop Differentiating Technique (HDT).

Different from the TMM algorithm, in HDT algorithm, we use a theoretical value of threshold rather than a trained threshold to detect evil twin attacks. In the theoretical computation phase, we theoretically compute a threshold α_θ as the SAIR boundary to differentiate one-hop SAIR and two-hop SAIR. Besides, in order to use SPRT technique, we also compute the upper bound for the probability of the SAIR exceeding the threshold α_θ in the normal AP scenario, and the lower bound for the probability of the SAIR exceeding the threshold α_θ in the evil twin AP scenario. The specific explanations about the computation of these three parameters will be discussed shortly.

In the detection phase, similar to the TMM algorithm, we also use SPRT technique to make the final decision. The main difference from TMM algorithm is that HDT algorithm uses the observed SAIR rather than IAT in one decision round to perform the threshold random walk.

3) *Threshold Setting For HDT Algorithm*: In this section, we develop a discrete numerical algorithm to theoretically compute the SAIR threshold α_θ for HDT algorithm, with a goal of minimizing the probability of making a wrong decision. According to Theorem 3 and 4, we can know that the threshold α_θ should be between 1 and 2. So, if we denote $P_1 = P(\alpha_{one-hop} \geq \alpha_\theta)$ and $P_2 = P(\alpha_{two-hop} \geq \alpha_\theta)$, the problem can be transformed to compute $E(\hat{\alpha}_\theta)$, s.t.,

$$\hat{\alpha}_\theta = \arg \min_{1 \leq \alpha_\theta \leq 2} (P_1 + 1 - P_2) \quad (12)$$

In the process of our computation, we let α_θ increase from 1 to 2 in fine-grained steps. In every step, we increase α_θ by 0.01 and compute $P_1 + 1 - P_2$. Once α_θ reaches 2, we can find the value of $\hat{\alpha}_\theta$ leading to the minimal $P_1 + 1 - P_2$. According

to 802.11 standard, we can derive the following results (details regarding to this computation can be found in our extended version [25]):

- If we consider the packets without any collisions, then,
 - for Protocol 802.11b, $\alpha_\theta = 1.31$, $P_1 \leq 21.8\%$, $P_2 \geq 76.9\%$;
 - for Protocol 802.11g, $\alpha_\theta = 1.48$, $P_1 \leq 27.3\%$, $P_2 \geq 71.5\%$;
- If we consider the packets whose collision numbers are under three, then,
 - for Protocol 802.11b, $\alpha_\theta = 1.34$, $P_1 \leq 21.2\%$, $P_2 \geq 74.9\%$;
 - for Protocol 802.11g, $\alpha_\theta = 1.48$, $P_1 \leq 27.3\%$, $P_2 \geq 71.2\%$;

C. Improvement by Data Preprocessing

In this section, we describe two data preprocessing techniques to improve the results: data filtering and data smoothing. For the first technique, we filter noisy data (according to the theoretical Server IAT) with large number of network collisions. For the second technique, we use the mean of multiple collected input data, rather than only one collected data, to smooth the input.

1) *Data Filtering*: In order to filter noisy data, we only consider the packets whose collision number is at most three. (According to [29], when the number of users is under 20, the probability that a packet has at most 3 collisions is over 85%). In this way, we can both filter the noisy data and keep sufficient data to implement the detection. Thus, according to IEEE 802.11 standard and our filter policy, we filter out the packets whose AP IATs exceeding $21,000\mu s$ or Server IAT exceeding $39,800\mu s$.

2) *Data Smoothing*: To further improve the result, we also use the mean of multiple input data rather than only one input data in one decision round. Specifically, we use the mean of multiple Server IATs or the mean of multiple SAIRs instead of only one Server IAT or one SAIR in one decision round to perform the threshold random walk. We name TMM algorithm and HDT algorithm using multiple Server IATs and multi SAIRs as multi-TMM algorithm and multi-HDT algorithm, respectively.

VI. EVALUATION

We evaluate the results and the performance of our evil twin attack detection algorithms through implementing a detection prototype system named ETSniffer (Evil Twin Sniffer). In this section, we describe our evaluation methodology, including the experimental setup, datasets, effectiveness, efficiency and cross-validation.

A. Implementation and Experimental Setup

We have implemented ETSniffer using Windows raw socket, since we need packet level control (including TCP parameters). As mentioned earlier, in order to guarantee the efficiency and accuracy of the computation of IAT, we adopt a new acknowledgment mechanism, named immediate-ACK policy.

We achieve the immediate-ACK policy by setting the TCP Maximum Segment Size (MSS) in the TCP header equal to the TCP Window Size. In this way, a TCP server should wait to receive the ACK packet for the previous data packet before sending out the next data packet. Note, since our immediate-ACK policy is only applicable to the specific probing connections initialized and controlled by ETSniffer, this policy will not devour network bandwidth. In addition, we use a fixed and small number for MSS setting in every connection to guarantee sufficient data packets received to detect evil twin attacks. By initiating TCP connection with customized TCP option and setting to make the server respond in the way we desire (e.g., sending packets with small size), ETSniffer can collect enough packets needed for detection even from a small-sized web page (which may only result in one or two packets in the normal setting).

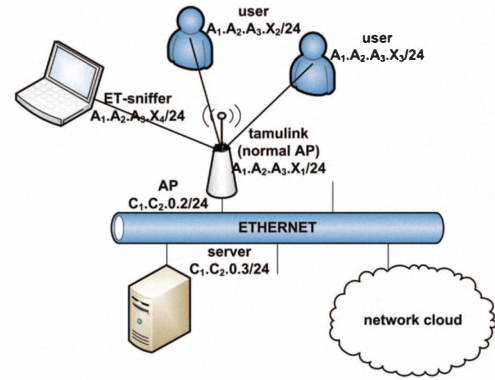


Fig. 5: Experimental environment setting for the evaluation of the normal AP scenario.

We set up our ETSniffer in the campus network of the Texas A&M University. To achieve user-side detection, we install ETSniffer in a laptop with a wireless network card. The ETSniffer can capture the packets, along with the current timestamp, to compute IAT and SAIR. To simulate a normal AP scenario, we use a laptop installed with ETSniffer as a user/detection client to communicate with a campus server through TAMULink (an official Texas A&M's campus wireless network Access Point). To simulate an evil twin AP scenario, we deploy another laptop as a wireless access point to act as an evil twin AP near to the detection client. The evil twin AP has the same SSID as the TAMULink, yielding a good RSSI to the detection client between 80% and 100%. And the evil twin AP connects to the server through the campus TAMULink AP. Thus, in this scenario, the detection client communicates with the server through a two-hop wireless channel. The actual experimental environment setting can be seen in Figure 5 and 6.

B. Datasets

We have collected data in real network environments, and built our datasets at different time and with different RSSI levels. To better evaluate our results, in our experiments, we denote different RSSI levels into 6 ranges: A, B+, B-, C+,

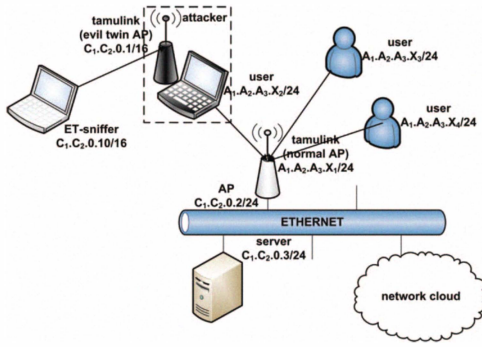


Fig. 6: Experimental environment setting for the evaluation of the evil twin AP scenario.

C-, and D, as illustrated in Table II. As described in Section

TABLE II: RSSI ranges and corresponding levels

Range	A	B+	B-	C+	C-	D	E
Upper	100%	80%	70%	60%	50%	40%	20%
Lower	80%	70%	60%	50%	40%	20%	0%

V-C1, we filter the packets whose collision numbers exceed three. The percentages of filtered packets are shown in Table III.

TABLE III: The percentage of filtered packets

Tech	Protocol	A	B+	B-	C+	C-	D
HDT	802.11g	0.80%	0.86%	3.91%	3.72%	4.69%	7.09%
	802.11b	1.38%	1.44%	5.61%	6.17%	9.42%	10.36%
TMM	802.11g	0.62%	0.68%	2.59%	2.66%	3.30%	6.02%
	802.11b	0.99%	1.04%	3.33%	4.82%	7.44%	8.29%

C. Effectiveness

We evaluate the effectiveness of our algorithms based on different RSSI ranges and two IEEE WLAN protocols – 802.11b and 802.11g. In the normal AP scenario, the RSSI refers to the link between the user and the normal AP; in the evil twin AP scenario, the RSSI refers to the link between the user and the evil twin AP. The results are shown in Table IV and V, which clearly verify the effectiveness of our algorithms. In addition, we can also find that the results obtained in 802.11g are better than those obtained in 802.11b. This is caused by the low bandwidth and larger initial window size in 802.11b protocol, leading to a larger variance of IAT distribution.

TABLE IV: Detection rate for HDT and TMM

	A	B+	B-	C+	C-	D
802.11g(HDT)	99.08%	98.72%	93.53%	94.31%	87.29%	81.39%
802.11b(HDT)	99.92%	99.99%	99.96%	99.95%	96.05%	94.64%
802.11g(TMM)	99.39%	99.97%	99.49%	99.5%	98.32%	94.36%
802.11b(TMM)	99.81%	95.43%	94.81%	96.09%	91.94%	85.71%

As described in Section V-C2, we use multi-TMM and multi-HDT to improve the results. The results of these two algorithms are shown in Figure 7. We can find that the detection rate increases with more input data in one decision

TABLE V: False positive rate for HDT and TMM

	A	B+	B-	C+	C-	D
802.11g(HDT)	2.19%	1.41%	2.06%	1.93%	2.48%	6.52%
802.11b(HDT)	8.39%	8.76%	5.39%	6.96%	5.27%	5.15%
802.11g(TMM)	1.08%	1.76%	1.97%	1.48%	1.75%	1.73%
802.11b(TMM)	0.78%	1%	1.07%	1.27%	6.65%	7.01%

round. But once the number of input data attains to some bound (in our experiment, the bound is 70), the performance become relatively steady.

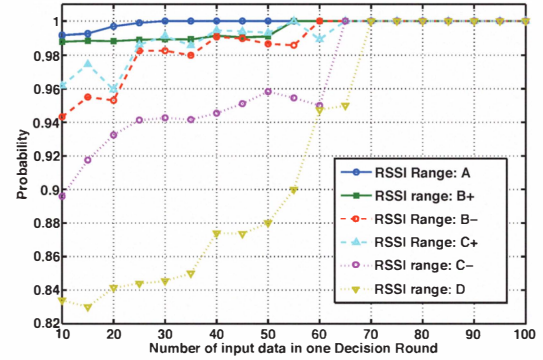


Fig. 7: Detection rate for multi-HDT using different numbers of input data in one decision round.

The results, obtained by setting the number of input data in one decision round as 50 and 100, are shown in Table VI, VII, VIII. From these tables, we can see that for both algorithms, the results computed by using 100 input data are better than that using 50 input data. Especially, when we use 100 input data in one decision round, we can get a nearly perfect result.

TABLE VI: Detection rate for multi-TMM and multi-HDT, when the number of input data in one decision round is 50

	A	B+	B-	C+	C-	D
802.11g(multi-TMM)	99.62%	100%	100%	99.95%	100%	100%
802.11b(multi-TMM)	100%	100%	100%	100%	100%	100%
802.11g(multi-HDT)	100%	99.11%	98.73%	99.88%	95.83%	88%
802.11b(multi-HDT)	100%	100%	100%	100%	100%	100%

TABLE VII: False positive rate for multi-TMM and multi-HDT, when the number of input data in one decision round is 50

	A	B+	B-	C+	C-	D
802.11g(multi-TMM)	0%	0.77%	0%	0%	0%	0%
802.11b(multi-TMM)	0%	0.03%	0.02%	0.11%	0.73%	0.1%
802.11g(multi-HDT)	0%	0.96%	0.16%	0.13%	0.55%	0.96%
802.11b(multi-HDT)	0%	1.07%	1.16%	1.02%	1.36%	1.41%

D. Time Efficiency

In this section, we evaluate the time efficiency of our algorithms. We use the average number of decision rounds to output a correct decision as the evaluation metric. We also use cumulative probability to express the process of the log-likelihood ratio to reach the bounds. The result is shown in Figure 8.

TABLE VIII: False positive rate for multi-TMM and multi-HDT, when the number of input data in one decision round is 100 (detection rate is always 100% in this case)

	A	B+	B-	C+	C-	D
802.11g(multi-TMM)	0%	0%	0%	0%	0%	0%
802.11b(multi-TMM)	0%	0%	0.01%	0.01%	0.02%	0.01%
802.11g(multi-HDT)	0%	0%	0%	0%	0%	0%
802.11b(multi-HDT)	0%	0%	0.02%	0.02%	0.03%	0.03%

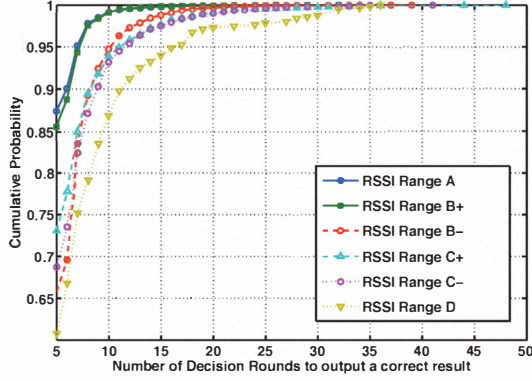


Fig. 8: Cumulative probability of the number of decision rounds for HDT algorithm to output a correct result.

From Figure 8, we can see that when RSSI is high, our HDT algorithm can output a correct decision within a few decision rounds. Although when RSSI drops, it needs more decision rounds, even under a low RSSI (e.g. RSSI range is D), our algorithm can obtain a correct result within 45 decision rounds, consuming a very short time. TMM has a very similar performance.

E. Cross-Validation

Form Section VI-C, we can find that both TMM algorithm and HDT algorithm demonstrate high efficiency and effectiveness. Especially, TMM algorithm, based on the trained knowledge, performs a little bit better than HDT algorithm. However, as described in Section V-A2, in many practical cases, the prior knowledge is difficult to be obtained. In addition, TMM algorithm does not accommodate well to the changes of the wireless network environment. Thus, to evaluate such limitations of TMM algorithm, in this section, we design cross-validation experiments under different levels of RSSI and different locations.

1) *Cross-validation under different RSSI*: In this section, we implement the cross-validation under different RSSI ranges. Specifically, we train the Server IAT threshold for TMM algorithm using the data from only one RSSI range and execute the detection phase using the data from all RSSI ranges. We show two scenarios in Figure 9 in this paper (a complete result can be found in [25]). From Figure 9, we can see that the detection rate drops dramatically, revealing TMM algorithm's tight dependency on the (perfect) training data.

2) *Cross-validation under different locations*: To validate the performance of TMM and HDT in different environments,

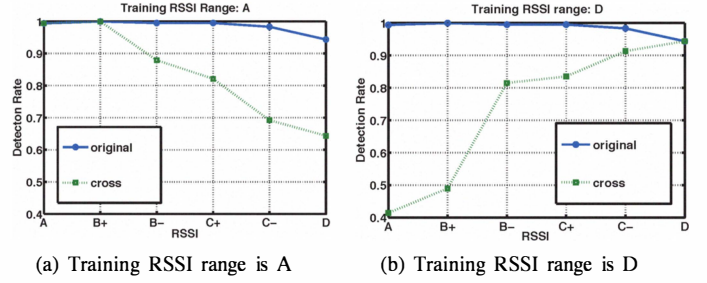


Fig. 9: The detection rate for TMM algorithm under different RSSI ranges.

we conduct a cross-validation under different locations. For TMM algorithm, we train the Server IAT threshold using the data collected in one wireless environment, and execute the detection in another location. From Figure 10 and 11, we can see that, if we train and test in different environments, the performance of TMM algorithm decreases obviously. However, the performance of HDT algorithm keeps steady.

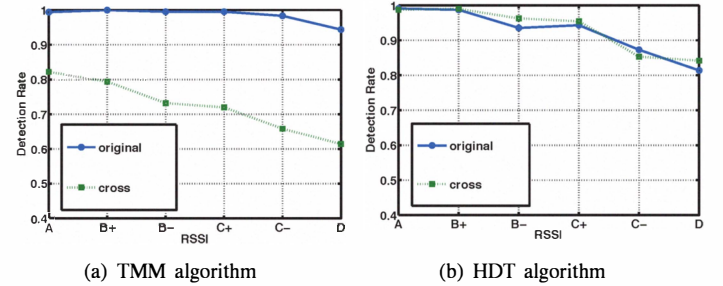


Fig. 10: Detection rate under different 802.11g networks.

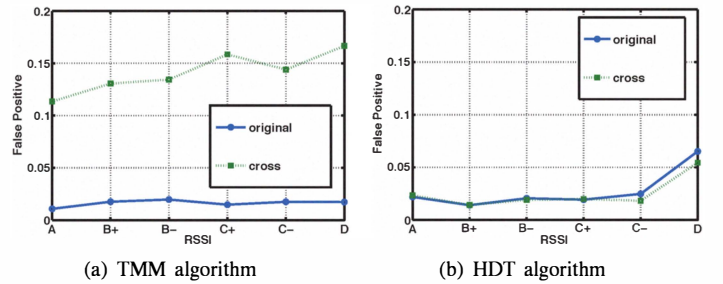


Fig. 11: False positive rate under different networks.

VII. DISCUSSION AND FUTURE WORK

Several relevant studies (e.g., [33], [34]) showed that the delays from the wired link is not comparable to those in the wireless link. In our experiment, the (remote) server is four (wired) hops away from the AP. While more wired hops will involve likely more “noise”, we note that SPRT technique can tolerate reasonable noise if we trade off for more decision rounds. In reality, we recommend to use a server within small hops. However, if the user has to use a server with many hops,

we could consider using techniques similar to “traceroute” to know the (wired) transfer time and then exclude/subtract them to minimize the (noisy) effect at wired side.

It is possible that once attackers know our algorithm, they attempt to evade the detection. Since they are in the middle of the user and normal AP, they can attempt to manipulate the packet relay time to affect IAT. They cannot decrease IAT, but they can delay the forwarding to increase IAT. For example, in order to evade HDT, the attacker should intentionally increase AP IAT to make it less differentiable than Server IAT. However, this actually violates the attacker’s intention to be a fast AP because the user will definitely favor an AP with good speed and if the evil twin chooses to do so it may lose the attraction to the victims. In addition, in such situation, the user is still easy to detect such anomaly by using TMM algorithm. Thus, we conclude that our detection algorithms are still reasonably effective.

Our current work focuses on evil twin AP detection, where the evil twin AP will utilize the normal AP to connect to Internet. This is a very realistic threat faced by public WLANs provided at airports, hotels, libraries, or cafes, etc. In our future work, we plan to extend our evil twin AP detection to more *general malicious* AP detection, where a malicious AP may not require the normal AP to relay traffic, or may not need to impersonate a normal AP. We also plan to study the problem in wireless infrastructures (e.g., 3G or WiMax) that have multi-hop legitimate wireless channels.

VIII. CONCLUSION

In this paper, we have proposed a novel lightweight user-side evil twin attack detection technique. We presented two algorithms, TMM and HDT. Through our prototype system implementation and extensive evaluation in several real-world wireless networks, we showed that our proposed technique is effective and efficient. HDT is particularly attractive because it does not rely on trained knowledge or parameters, and is resilient to changes in wireless environments.

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