Rejecting the Attack: Source Authentication for Wi-Fi Management Frames using CSI Information

Zhiping Jiang*, Jizhong Zhao*, Xiang-Yang Li†, Jinsong Han*, Wei Xi*
*School of Electronic and Information Engineering, Xi'an Jiaotong University, Xi'An, China
†Department of Computer Science, Illinois Institute of Technology, Chicago, IL
Email: {*jiangzp.cs, weixi.cs*}@gmail.com, *xli*@cs.iit.edu, {*zjz,hanjinsong*}@mail.xjtu.edu.cn

***Abstract*—Comparing to well protected data frames, Wi-Fi management frames (MFs) are extremely vulnerable to various attacks. Since MFs are transmitted without encryption or authentication, attackers can easily launch various attacks by forging the MFs. In a collaborative environment with many Wi-Fi sniffers, such attacks can be easily detected by sensing the anomaly RSS changes. However, it is quite difficult to identify these spoofing attacks without assistance from other nodes.**

By exploiting some unique characteristics (*e.g.*, rapid spatial decorrelation, independence of Txpower, and much richer dimensions) of 802.11n Channel State Information (CSI), we design and implement *CSITE*, a prototype system to authenticate the Wi-Fi management frames on PHY layer merely by one station. Our system CSITE, built upon *off-the-shelf* hardware, achieves precise spoofing detection without collaboration and in-advance fingerprint. Several novel techniques are designed to address the challenges caused by user mobility and channel dynamics. To verify the performances of our solution, we conduct extensive evaluations in various scenarios. Our test results show that our design significantly outperforms the RSS-based method. We observe about 8 times improvement by CSITE over RSS-based method on the falsely accepted attacking frames.

I. Introduction

Wi-Fi technology is on its rapid evolution. IEEE 802.11n and its successor 802.11ac supports more than 600Mbps throughput. 802.11i amendment, or WPA2 encryption, provides safe data exchange. However, an attacker can still launch Denial of Service (DoS) attacks [1]–[3] easily, breaking the connection between AP and client, establishing rogue AP, and even performing Man-In-The-Middle (MITM) attack. To varying degrees, all these attacks exploit a main vulnerability of the 802.11 system, that the Management Frames (MFs), which are indispensable to the normal operation of Wi-Fi, has not been protected by any security measures [4]. Hence, attackers can forge the MFs simply using a laptop with an injection-enable wireless NIC.

Sequence Number (SN) based spoofing detection can be bypassed if the SN of attacking frames follows the original pattern. IEEE 802.11w amendment seeks to protect several key MFs by encryption-based authentication, it still has some vulnerabilities identified in recent researches [5], [6]. The Mac address spoofing attacks can be easily detected by Wireless Intrusion Detection System (WIDS) or similar systems [7]–[9]. The power of WIDS roots on the collaboration of many Wi-Fi sensors dispersed in the environment. These sensors overhear the Wi-Fi traffic and cooperate in detecting the anomaly Received Signal Strength (RSS) variation for the same MAC addresses. However, due to its high deployment cost, WIDS is not common for public environment. Because of its high correlation with transmit power (Txpower) and distance, RSS is naturally more suitable for localization [10]–[13] rather than spoofing detection. Hence, without collaboration from other nodes, RSS-based spoofing detection can be bypassed by Txpower scanning.

In search of a MFs authentication mechanism which supports operating independently on a single station, we focus on the 802.11n PHY-layer information, Channel State Information (CSI), which is a large complex-number matrix that reveals the Channel Frequency Response (CFR) for each subcarrier of the underlying 802.11a/g/n OFDM system. CSI has some unique advantages, *e.g.*, rapid spatial decorrelation, independence of Txpower, and rich data dimensions. After some proof-of-concept experiments, we believe CSI is an ideal alternative to RSS-based spoofing detection.

Based on these advantages, we design **CSITE**, a CSI-based management frame authentication system using *off-the-shelf* NICs. The idea is simple yet effective: regardless of the frame type, data or management frames the transmission between AP and legitimate stations undergoes the same channel fading. Consequently, their CSI are exactly the same. If an attacker injects a forged MF, the CSI of this frame must be quite different to the CSI trend learnt from previously accepted frames, thus we consider that this frame is suspicious.

Our CSITE system is based on a reasonable security assumption that the data frames with strong encryption, *e.g.*, WPA2 under AES encryption with a strong password, is very hard to be cracked in a relatively short time [14]. As a result, an attacker cannot forge a data frame that can be correctly decrypted by legitimate stations, hence the encrypted data frames which are correctly received and decrypted are considered to be sent from genuine stations, and the CSI of these frames are deemed to be the fingerprint of the wireless channel between genuine stations.

Despite an elegant solution, there are three main challenges that should be carefully addressed:

First, compared to one-dimensional temporal RSS data, the CSI information for each frame is a large complex number matrix of the size $N_{tx} \times N_{rx} \times 30$, where N_{tx} and N_{rx} denote the number of transmitting and receiving antennas respectively. Learning the CSI pattern and Identifying anomaly data points in such a high-dimensional data stream are big challenges when the frame receiving rate f_r is high.

Second, it is the spatial decorrelation that makes CSI unforgeable, but this also makes the authentication intolerable to frequently-happened channel dynamics, *e.g.*, those caused by crowd flow or user mobility. In such conditions, there are inevitably some genuine MFs that are rejected. A mechanism should be carefully devised to guarantee the delivery of every genuine MF.

Third, transmitting all frames in "HT" rate is allowed in 802.11n Sepc., and it is indispensable for measuring CSI. However, most MAC layer implementation still use the 802.11a/g compatible code which transmits the MFs in *legacy* rate.

In our work, an accurate and efficient CSI-based attacking detector is first designed. Since MF only occupies a small portion of normal traffic, high accuracy checking can be achieved without affecting network throughput. To cope with the channel dynamics, we devise a method called "CSI Resolution Enhancement" (CRE) to ensure the transmission of legitimate MF even under highly intensive channel dynamics. Since it is standard-permitted and technically possible for sending management frames in "HT" rate, we modify the MAC layer implementation and NIC drivers to enable the transmission of management frames in "HT" rate.

In summary, the main contributions of this paper are as follows. We design CSITE, a cross-layer system based on CSI to perform PHY-layer source authentication for Wi-Fi management frames. In addition to the natural advantages of single-station accurate authentication, CSITE can also cope with user mobility, and no cooperation or in-advance fingerprint is required. We implement a prototype of CSITE using the off-the-shelf hardware and conduct extensive studies on the performance of our method in various scenarios. Our evaluations show that CSITE has excellent performance on accuracy, robustness, and efficiency. It significantly outperforms the RSS-based method in the same scenarios. For example, when the client and the attacker are walking with regular speed, CSITE accepts some attacking frames with probability about 2%, while RSS-based method accepts attacking frames with probability about 18% for the same scenario. When only the client is moving, we observe similar improvement (about 8 times) by CSITE over RSS-based method on the falsely accepted attacking frames. A more significant improvement is obtained in stationary scenarios, see Section IV for details. To the best of our knowledge, we are the first to exploit the unique characteristics (*e.g.*, rapid spatial decorrelation, independence to Txpower, and rich dimensions) of *off-the-shelf* platform's Channel State Information (CSI) for authenticating management frames in Wi-Fi networks.

The rest of the paper is organized as follows. Section II presents some preliminaries and reviews related works. Section III describes the CSITE system design. A series of experimental results and analysis are shown in Section IV. We discuss the compatibility and other security issues in Section V and conclude the paper in Section VI.

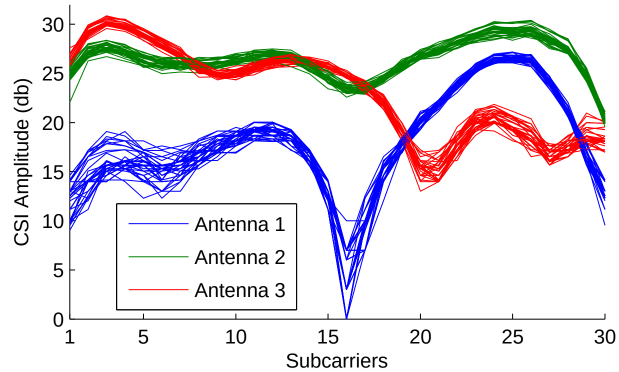


Fig. 1. An example of CSI data. Since Intel 5300agn NIC has 3 antennas, there will be 3*30 subcarriers information for each MAC layer frames. For visual clarity, here we show only 40 frames.

II. Background and Related Work

In this section we first give a brief review of OFDM, CSI, and 802.11n, which are the foundations of CSITE design. Then a review of related works are presented.

A. OFDM, 802.11n, and CSI

802.11a/g/n adopt Orthogonal Frequency Division Multiplexing (OFDM) technology. In OFDM, the overall wide bandwidth channel is divided into many small but orthogonal sub-carriers. Thus for OFDM system, channel estimation is equivalent to measuring the parameters of all the subcarriers. In 802.11n and its successor 802.11ac, Channel State Information (CSI) is a large complex-number matrix which describes the channel frequency response (CFR) for each subcarrier in every spatial stream. Each complex value h in CSI matrix could be transformed to polar coordinates that

$$h = |h| \, e^{j\angle h}$$

where $|h|$ and $\angle h$ denote the amplitude and phrase of each subcarrier. Fig. 1 presents the amplitude of CSI samples.

B. Related Works

Numerous researches claim to have the ability to detect MAC-layer spoofing attacks based on RSS or Sequence Number (SN). However, Txpower can be adjusted to forge the same RSS level, while SN could be forged by following the original pattern. Fingerprint based on hardware transceiver profile is thought to be a perfect solution [15], but advanced attacker using arbitrary waveform generator, can still compromise the fingerprint [16].

Wireless Intrusion Detection System (WIDS) or similar systems [7], [17], [18] can provide reliable attacking detection in secured environment, but these approaches are limited due to the deployment of monitor stations. To the best of our knowledge, the most advanced RSS-based detection is the RCVI [19]. This work cleverly exploits the reciprocity of RSS variance in mobile wireless networks. By detecting the mis-matched RSS variation, an Identity-based Attack (IBA) is detected. However, RCVI require the sender to report the RSS records of the latest received ACK frames, which is a slightly high requirement.

There are growing interests in authentication, location distinction and even localization based on physical layer information. Channel Impulse Response (CIR) has been used to provide robust location distinction in [20], [21]. There are some works [22]–[24] that went further trying to provide precise indoor localization either by identifying the Line-Of-Sight components or by identifying cluster information in CSI.

A new attack against PHY-layer authentication called *mimicry* was identified in [25]. However, such attack is neither easy to launch due to the existence of *symbol sensor*, and it is not likely to succeed due to the MIMO configuration which introduces richer channel information.

III. CSITE Design

In this section, we will first present some of our observations on which the design of CSITE are based. Then the design of CSITE is presented in details.

A. CSI for Packet Authentication

CSI, in contrast to RSS, decorrelates with spatial position quite rapidly [26]. The correlation efficient ρ between two CSI samples may quickly drop to 0 if the sampling locations are apart merely more than half a wavelength. It means once sufficiently distant, an attacker cannot estimate the victim's CSI based on the CSI measured locally. Besides the decorrelation with position, CSI also has very low correlation with Txpower, therefore the traditional Txpower-scanning attacks cannot fool CSI-based detection. Third, CSI is a high-dimensional data [27]. For a 3×3 802.11n MIMO transferred frame, there are 270 values in the CSI matrix. Apparently it is of great difficulty to forge the CSI even under most sophisticated preparation.

A simple attack experiment is conducted to observe the characteristics of CSI. We collected 3000 frames, among which the first 1500 frames are from legitimate station, while the following 1500 frames include frames from both attackers and legitimate station. Fig.2 (a) shows the CSI amplitude of the sample packets, where different colors denote different amplitudes. We can see the attacker starts injecting a group of attacking frames periodically after the 1500th frame, and the visual difference between the legitimate and injected frames is very clear. Fig.2 (b) shows the empirical probability density function (PDF) of subcarrier 20 collected from the first 1500 frames by directly plotting the $Re(h)$ and $Im(h)$ dots, where h is the CSI for this subcarrier. Since the amplitude is stable during the test and the phase is distributed between 0 to 2π, we observed a ring-shaped structure with narrow width. Fig.2 (c) shows the PDF of all the CSI for subcarrier 20. Due to the amplitude difference between the legitimate and injected frames, a double-ring shaped structure is presented. Such amplitude difference can be used to detect the attacking frames.

B. CSITE Architecture

We are now ready to discuss the architecture of our *CSITE* prototype for authenticating MF frames in Wi-Fi environment.

The CSITE system consists of two parts: *CSITE filter* and *MF transmission assurance system*. The CSITE filter implements our CSI-based spoofing detection algorithm, and its goal is to detect and reject any suspicious MFs. However, the safety and efficiency are always contradictory. In dynamic environment, CSITE filter may also reject some legitimate MFs. In such case, the sender should take measures to ensure the successful delivery of legitimate MFs without compromising the security standard of receiver's CSITE filter, and this is achieved by the MF transmission assurance system.

Since routine data frames are naturally used to update CSI pattern, we don't exert extra burden to network traffic. However to cope with the burst of transmission and asymmetry between uplink and downlink, we set a maximum interval T_{im} between two CSI updates. Once a station has not been updated for a time duration exceeding T_{im}, it will send a ICMP "Probe Request/Reply" probe to force a CSI probe. Then the update frequency, denoted as f_s, of a station would be $max(1/T_{im}, f_{dl})$, where f_{dl} denotes the downlink data frames frequency.

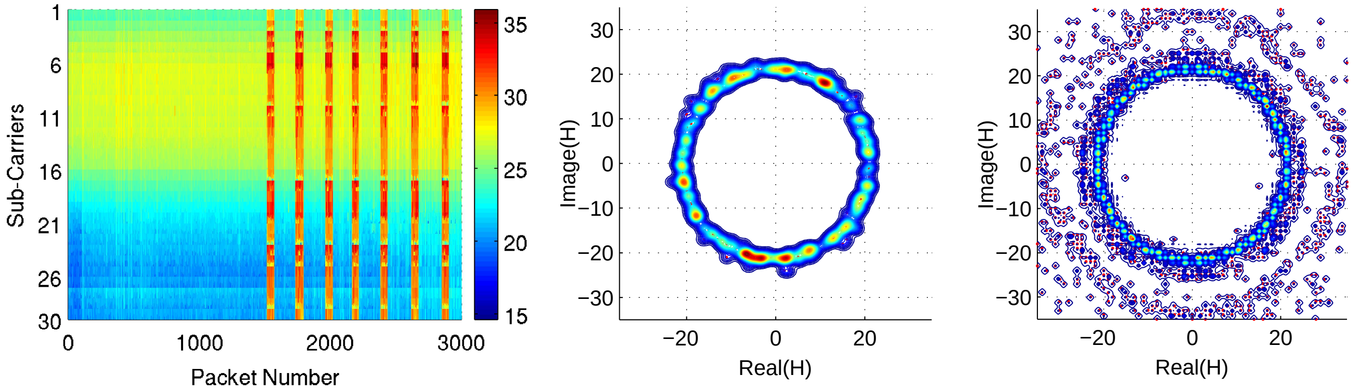
C. CSITE filter

The mission of CSITE filter is quite clear. Let S_Y denote the frame stream received by a station, and S_Y is composed of three parts: $S_Y = \{S_d, S_m, S_{in}\}$. Here $\{S_d\}$ and $\{S_m\}$ are the encrypted data frames stream and management frames stream sent from genuine station, respectively. $\{S_{in}\}$ is the forged frames stream sent by attackers using injection tools. Our mission is to determine, for each newly arrived management frame M, whether it's sent from genuine station or attacker based on the CSI pattern learnt from S_d. On designing such an filter, there are two technical requirements:

• **Low False Positive (FP) error:** Classifying frames into "legitimate" or "suspicious" frames may introduce two errors: wrongfully accepting an attacking frame (called false negative (FP) hereafter), and wrongfully rejecting a legitimate frame (called false Negative (FN) hereafter). Since re-transmission can be launched once a delivery fails, the FN error is tolerable to some extent. However, due to the high risk of successive attacks (*e.g.*, man-in-the-middle attacks) triggered by some spoofing attacks, such as de-authentication attack, the FP error is absolutely not acceptable.

• **Low overhead:** In a real world environment, network throughput could be very high, large computation and communication overhead for attacking detection will significantly degrade the network performance.

Due to the rapid spatial decorrelation, the CSI of spoofing frames are highly probable to be "distant" from the CSI of



(a) CSI sample with injection (b) PDF for SC20 (first 1500 frames) (c) PDF for SC20 (all data)

Fig. 2. (a) Amplitude of CSI sample where warmer colors denote larger amplitudes. Attacking frames are injected starting from frame number 1500. (b) PDF for sub-carrier 20 of the first 1500 frames, where the value (denoted by colors) at a point is the number of frames with this CSI. (c) PDF for sub-carrier 20 of all samples, including attacking frames.

legitimate frames. Thus, detecting spoofing frames can be viewed as an online anomaly detection problem and the goal is to identify such "distant points".

K-Nearest Neighbor (KNN) [28] is a common solution for high-dimensional anomaly detection [29]. Notice that because a MF frame is said to be suspicious if it significantly deviates from the trend of *most recently* accepted frames, the “anomaly” detection for the problem studied in this paper also needs to consider the temporal distance of the frames. Thus, traditional KNN algorithms cannot be directly applied here. To reflect the impact of the timing characteristics of all frames, our distance metric takes both spatial and temporal distance into account. An self-adaptive threshold is determined to classify a CSI point into two categories "trusted" or "suspicious". However, before introducing the algorithm, we should first reduce the data point dimension.

Dimensionality Reduction: Due to the high dimensions of CSI data point, it will consume large computational resource to perform anomaly detection if all dimensions are taken into consideration. Even we set the MIMO Tx-antenna $N_{tx} = 1$ and Rx-antenna $N_{rx} = 3$ for our prototype, the dimension of the CSI data point for each frame is $Dim(S_H) = N_{tx} \times N_{rx} \times 30 = 90$, which is still too large, especially for AP, which is going to handle multiple connections.

As *phase* is distributed between 0 to 2π which provides no discriminative information, the complex number data point H is first reduced to a real number data point containing only the amplitude $A = |H|$. Since amplitudes of subcarriers exhibit certain continuous structure as shown in Fig.1, we can further merge the adjacent amplitudes. In our system, every 2 adjacent amplitudes are merged to their mean as $(A_i + A_{i+1})/2$.

Frame Authenticity Verification: To verify the claimed authenticity, each receiver holds a sliding window W_r to store the latest verified CSI points with a length L_W. Determining whether a MF is from genuine station is equivalent to determining how distant a MF is from to the CSI trend in W_r. If the incoming MF frame perfectly follows the trend, it is highly likely to be a true MF; otherwise it is *suspicious*. We will use the "*degree of following*" (DoF) (exact definition will be given later) to characterize how closely a newly received MF M follows the trend defined by frames in the sliding window W_r. This DoF is determined by two factors: the distance to its k nearest points in the window W_r and the time difference between M's arrival time t_M and the arrival time of its k nearest points.

Suppose there are n dimensions in each data point after *dimensionality reduction*. We first define the Euclidean distance between CSI point A and B as $dist(A,B) = (\sum_{i=1}^{n}(A_i - B_i)^2)^{\frac{1}{2}}$. The *following coefficient* between these two points is defined as follow:

$$fc(A,B) = e^{\lambda(|t_A - t_B|)}$$

where λ is a constant called **time gain factor** and t_A denotes the arrival time of point A. We then define the "time-gain distance" between point A and B as

$$tgd(A,B) = dist(A,B) \cdot fc(A,B)$$

Let $N_k^{tgd}(M, W_r) = \{P_1, P_2, \cdots, P_k\}$ be the k-NN of M from the sliding window W_r under the TGD distance. The "*Degree of Following*" (*DoF*) of a new arrival management frame M is then defined as

$$DoF(M) = \frac{\sum_{i=1}^{k} tgd(M, P_i),}{k} | P_i \in N_k^{tgd}(M, W_r) \quad (1)$$

Dynamic Threshold Scaling (DTS) : We use threshold τ to decide whether to accept a newly arrived frame M: the M is considered to be legitimate **iff** $DoF(M) < \tau$. Recall that the premier goal of CSITE is to prevent FP error, the τ should be adjusted adaptively to defend attacks even under highly dynamic environment. Based on a reasonable assumption that the *DoF* of a newly arrived legitimate MF M is highly probable to be similar to the *DoF*s of the recently accepted frames. Thus in our system τ is determined according to the latest DoFs. Let $Q_b(W_r)$ denote the most recently accepted b-th point in the window W_r. Instead of using simple mean or median, the τ is set to i-th percentile of DoFs of recently accepted points, âĂćet al.

$$\tau = p_i(\{DoF(Q_b(W_r)) \mid 1 \leq b \leq k\}) \tag{2}$$

where $p_i(S)$ denotes the ith percentile function. Although Eq. (2) requires $k \times L_w$ calculation, it can be optimized by pre-caching the distance matrix between points P_i and P_j.

Here the right selection of percentile i is vital for the system. When there is little channel dynamics, average *DoF*s of recently accepted frames could be very low. It may cause more FN error (reject the legitimate MF), thus slightly higher i is preferred. While there is intensive channel dynamics, average *DoF*s of recently accepted frames could be very high. In such case the *DoF* of a legitimate MF is not necessarily lower than the *DoF* of an attacking frame, thus lower i is preferred for security concerns. An negative correlation between i and *Channel Stability* is needed.

In CSITE, we define the channel stability σ_W as the mean of the standard variance of the differences between two adjacent CSI points that

$$\sigma_W = \overline{(std_n(|P_j - P_{j+1}|))}, n \in [1, Dim(P_i)], j \in [1, L_w - 1]$$

where std_n stands for the standard variance for nth dimension of the CSI in window. We then define an effective negative correlation between i and σ_W as $i_1 = \dfrac{i_0}{\sigma_W / \sigma_W^r}$, where i_0 is set to 75 as default, and σ_W^r denotes the reference σ_W, which is measured during the CSITE initialization.

Based on the definition of $DoF(M)$, τ, and i, we design our source authentication algorithm as shown in Algorithm.1.

Algorithm 1 Spoofing Frame Detection Algorithm

Input:
The CSI amplitude of a newly received frame H;
The encryption property of H,
$attr_{en}(H) \in \{encrypted, unencrypted\}$

Output: A security classification of H,
$attr_{sec}(H) \in \{trusted, suspicious\}$

```
for each new arrival frame H do
    if attr_en(H) == encrypted then
        sliding window W_r move forward to include H
        attr_sec(H) = trusted
    else
        calculate the DoF(H) according to eq.1
        calculate the τ according to eq.2
        if DoF(H) ≤ τ then
            sliding window W_r move forward to include H
            attr_sec(H) = trusted
        else
            attr_sec(H) = suspicious
```

D. MF transmission assurance system

Due to the rapid spatial decorrelation and the negative correlation between i and σ_W, the CSITE filter is more likely to reject than to accept any suspicious frames. In dynamic environment, it is even harder to classify a MF into "trusted" due to the large noise. How to guarantee the delivery of legitimate MFs in any case is a big problem.

Despite rapid spatial decorrelation, wireless signal propagation can be well modeled as an analogue continuous system. In this system when sampling rate $f_s \to \infty$, the differences between each sampling $\Delta D \to 0$. It means when the frame rates is high enough, we can see very smoothed and slow-changing CSI amplitude surface under intensive channel dynamics. Fig. 3 presents a proof-of-concept experiment. During the experiment, large files are transmitted in HT rate between fast-moving stations, Fig. 3(a) presents the temporal CSI data of a station. When we gradually zoom into the details specified by the black rectangle, we see very smooth surface just like in static environment.

Based on the observation, we design a method called "CSI Resolution Enhancement" (CRE) to guarantee the delivery of MF. The core of CRE is that: if we transmit an unprotected MF M immediately after a group of high frequency "precursor" data frames, there will be smoothed amplitude surface in W_r and receiver's CSITE filter will think it is in a static environment and accept the M by setting higher i. The sender repeats this procedure until the delivery succeed.

Formally speaking, for each MF M to be transmitted, we define a frame stream $S_j = \{D_0, D_1, ..., D_{l_j}, M\}$ with minimum transmission interval between frames, where D_i are encrypted data frames. S_j is the j-th transmission procedure. We repeat this procedure until the frame M is successfully transmitted.

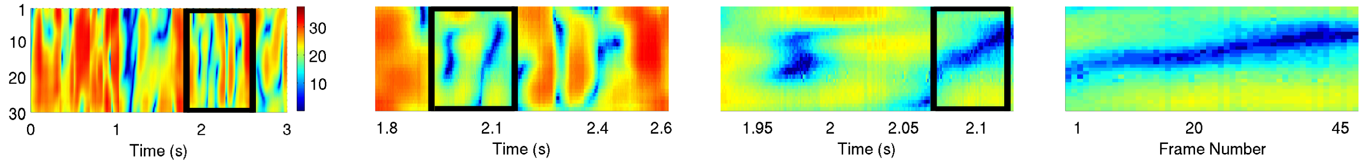
Since the proportion of MF in normal communication is small, we adopt a simple yet robust power-based scheme to guarantee the delivery. Suppose both sides keep the same k and L_W, the l_j is expected to be:

$$l_j = 2^j \times (l_1 + 1), j \in (2, 3..., N), l_j \leq L_W \tag{3}$$

This scheme simplifies the problem, and we only need to determine the initial value l_1, which is a fixed value in current prototype.

Negative ACK encapsulated in Echo Request: There is a firmware-level limit: we have no control on the transmission of ACK frame. The firmware will emit the ACK frame even if the frame is rejected by the CSITE filter, therefore transmitter cannot determine if the delivery is successful.

We adopt an *ad hoc* solution to inform the transmitter. Every time a frame does not pass the CSI filter, the receiver will immediately send a *Negative-ACK* to inform the sender. Such N-ACK is carried in a ICMP "ECHO REQUEST" frame whose echo content indicates the the failed frame type and sequence number, like "PROBE_REQUEST@42316". Since the frame is encrypted, only genuine transmitter can learn this N-ACK and start re-transmission as described above. However



(a) 100% view (b) 375% zoomed view (c) 1500% zoomed view (d) 6000% zoomed view

Fig. 3. (a). Original view of CSI under highly dynamic environment. (b), (c), and (d) provide gradually zoomed views for the details circled by black box.

if such N-ACK emits for a spoofing attack, the genuine station will be aware of being forged and may trigger alarm.

We mention again that this *ad hoc* solution exists only because we have no control on the ACK frames.

IV. Prototype Evaluation and Analysis

A. Prototype System Setup

Our prototype system consists of 3 laptops equipped with Intel 5300 NICs. Two of them form an AP-Client network, and the rest one acts as an attacker. Their drivers are all modified to enable them to transmit (or inject) management frames in HT rate in compliance to IEEE 802.11n standard.

B. Attacking Test Setting

In order to fully evaluate the performance of CSITE filter and make comparison to RSS based detection, we designed test cases and applied them in 7 typical scenarios. The description of them is presented in Table I. Scenarios A, B, and C test the performance when the client is stationary while channel dynamics are gradually increasing. D to F test the performance when client is moving with different speeds. G presents the last test that both client and attacker are moving.

TABLE I
Test Scenarios Description

A	Both the client and attacker are stationary in a controlled environment.
B	Same as A, but there is some channel dynamics caused by crowd flow.
C	The client is stationary, while the attacker is moving around. No crowd flow.
D	The client is moving, while the attacker is stationary. speed is normal.
E	The same as D, but moving speed is slow.
F	The same as D, but moving speed is fast.
G	Both the client and attacker are moving, speed normal.

We run a test for each scenario and each test lasts for 5 minutes. During the test, the AP and the client are continuously updating the CSI pattern using the *ping* command. Besides the data stream generated by ping command, the client initiates 20 Probe Requests to the AP every 0.3s, and the AP replies 20 Probe Responses to the client immediately. Both Probe Request/Response are MFs and they form the un-encrypted stream S_m.

The attacker uses *aireplay-ng* to inject 64 forged de-authentication frames to the client every 0.5s using the AP's MAC address. During the attack, the Txpower is scanning from 1dBm to 15dBm in a loop. For the sake of convenience, we set a switch in the client to prevent the connection being really de-authenticated once the client wrongfully accepts the forged de-authentication frames.

For each test case, we mainly focus on two error rates: FP error rate and FN error rate. Specifically, the FP error rate is the number of de-authentication frames which are considered to be sent from legitimate station over the totally received number of de-authentication frames. Similarly, the FN rate is the number of Probe Responses that are considered to be suspicious over the totally received number of Probe Responses.

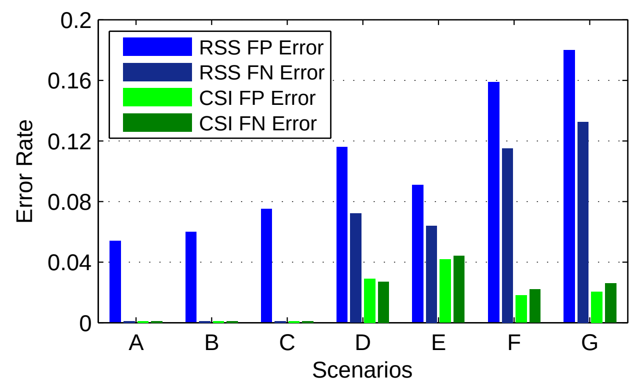


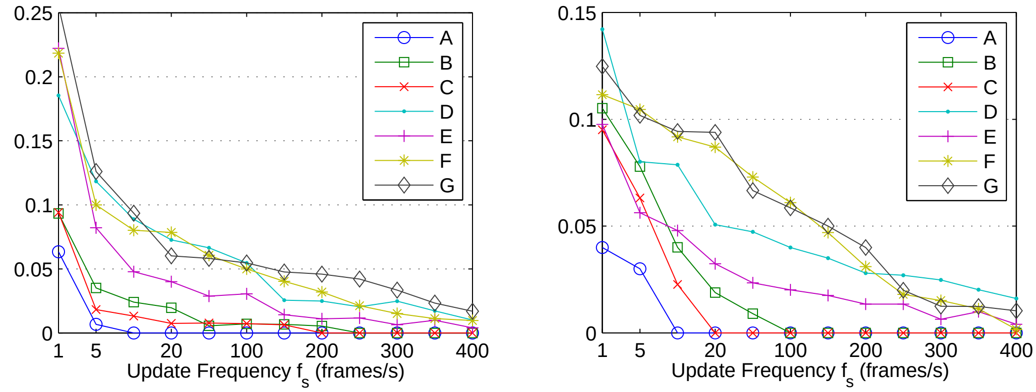
Fig. 4. Error rates comparison between CSITE and RSS-based detection

C. Compared to RSS-based Authentication

To make a fair comparison between CSITE and RSS-based detection, we turn off the dynamic threshold scaling (DTS) function and set the default value for $i = 75$. Fig.4 presents the error comparison between CSITE and RSS-based detection in different scenarios. In stationary scenarios A, B, and C, due to the strong measurement noise, RSS-based detection yields an FP error rate about 6%, while CSITE achieves perfect 0 FP error rate. In motion scenarios, CSITE accepts only about 2% attacking frames, while RSS-based detection accepts more than 17% attacking frames. It is about 8 times improvement made by CSITE over the RSS-based detection.

D. Impacts of various parameters

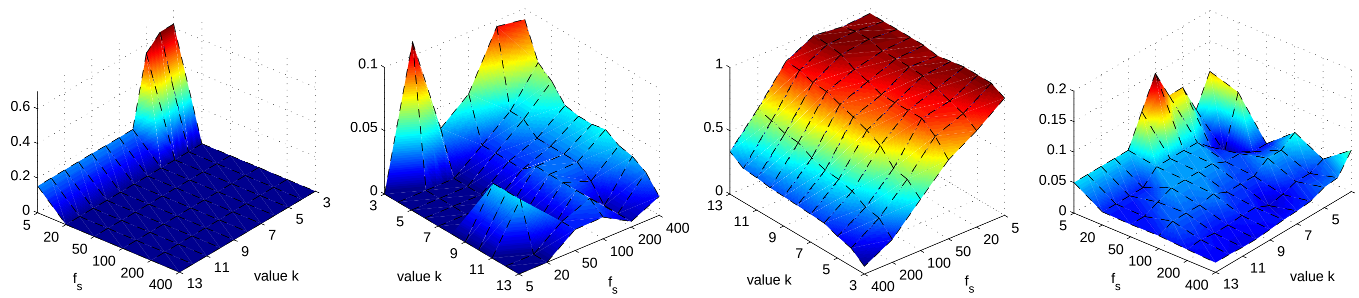
To identify the impacts of various parameters, we still turn off the *DTS* function and use default values $k = 5$, $\lambda = 1$, $L_w = 40$, $i = 75$ for the rest of evaluations if not specifically mentioned.



(a) FP error rate

(b) FN error rate

Fig. 5. Impacts of update frequency on dete52ction error rate. Both the FP and FN errors decrease when update frequency f_s is increasing. In Scenarios A, B, and C, both the error rate quickly converge to 0, while for Scenarios D, E, F, G, higher frequency are needed to cut down the error rate.



(a) FP error rate for A

(b) FN error rate for A

(c) FP error rate for G

(d) FN error rate for G

Fig. 6. The combined impacts of value k and update frequency f_s in two scenarios A and G. (a) and (b) show the FP and FN error rates for Scenario A, and (c) (d) for G.

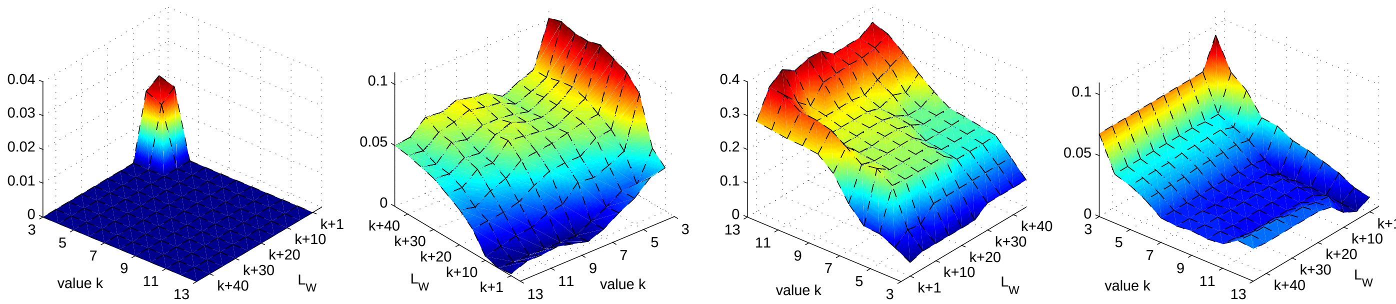
1) Impact of update frequency f_s: To test the impact of f_s, we vary the sampling rate f_s from 1Hz to 400Hz by uniformly dropping frames in the data stream. Fig.5 illustrates the FP and FN error rates in different scenarios when f_s is increasing. In stationary scenarios, the FP and FN error rates drop to 0 rapidly when f_s is increasing. For motion scenarios, the FP error rate drops to about 5% when $f_s \geq 100$Hz. When $f_s \geq 400$Hz, the FP error rate is not higher than 3% even under most intensive dynamics in scenario G.

However, we should mention that in normal communication the *DTS* function is turned on, the CSITE filter could reject almost all attacking frames even when f_s is very low, as verified by our results in *Impact of Dynamic Threshold Scaling*.

2) Impact of the number of nearest neighbors k: Fig.6 shows the combined impact of k and f_s on the error rate in scenarios A and G. Since τ is partly determined by the *time-gained distance* of the latest accepted points, k and f_s play an important role for deciding which points are taken into account. According to Fig.6(a) and (b), higher k could reduce the error rate when in stationary situation. In motion scenarios, however, lower k is better. This is because higher k in this case will introduce more non-related CSI points, which become noises when determining the τ. Based on the test conducted in all scenarios, we believe $k = 5$ is a suitable value for both the stationary and the motion scenarios.

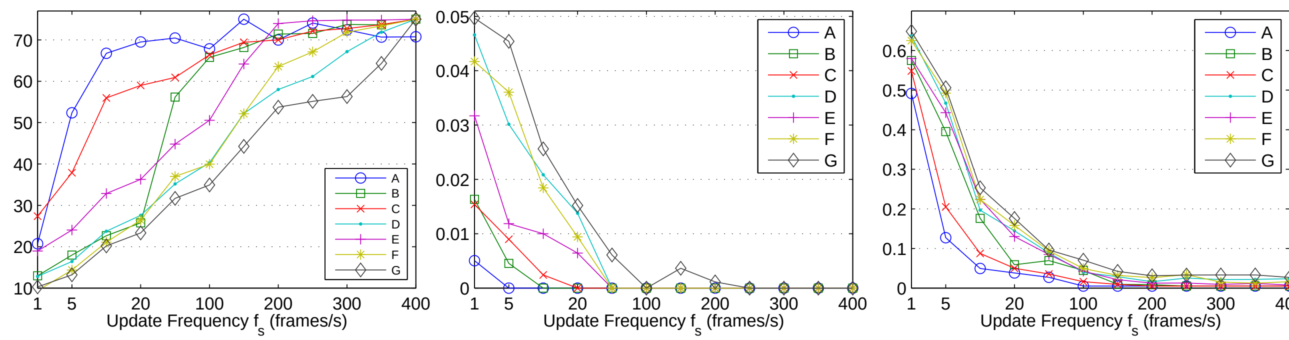
3) Impact of sliding window length Lw: Fig.7 presents the combined effect of sliding window length L_W and k on scenarios A and G. In both the stationary and the motion situations, increasing L_W is generally good for reducing error rate, but the marginal effect is reduced since the CSITE filter is tuned to choose the most recently accepted points. When $L_W > 40 + k$, the benefit of increasing L_W can be ignored in all scenarios, therefore we set $L_W = k + 40$ for both accuracy and efficiency.

4) Impacts of Dynamic Threshold Scaling: Apparently, lower threshold τ determined by i rejects not only the attacking frames but also some legitimate frames which deviate from the trend center. However, a lower i is preferred since the premier goal of CSITE is to reject the attacking frames. Recall the *DTS* function introduced in Section III, Fig.8(a) shows the average window variance $\overline{\sigma_W}$ for different scenarios and frequencies. Fig.8(b) shows the dynamic percentile i calculated according to σ_W. The impact to the error rate is shown in Fig.8(c) We see that the FP error rates quickly drops to 0 in stationary scenarios. For the most dynamic scenario G, FP error rate drops to astonishingly 5% when $f_s = 5$Hz, and The FP error rates drop to 1.53% when $f_s = 20$Hz.



(a) FP error rate for A (b) FN error rate for A (c) FP error rate for G (d) FN error rate for G

Fig. 7. The combined effect of value k and sliding window length L_w on error rate under two scenarios A and G.



(a) Scaled Percentile i (b) FP error rate (c) FN error rate

Fig. 8. (a) shows the calculated percentile i according to σ_W. (b) and (c) present the corresponding FP and FN error rates using the percentile i shown in (a).

E. Evaluation on MF transmission assurance system

To fully evaluate the transmission of MF in different f_s and scenarios, the data frames before the precursor frames are randomly dropped to simulate different f_s, and the length of precursor frames L_{pre} varies from 0 to L_W.

Fig.IV-E(a) and (b) present the MF transmission success rate comparison with different amount of precursor frames in scenarios A and G. Since *DTS* function is turned on, many FN errors are generated when f_s is low. However, with the help of precursor frames, we can see that even when $f_s = 5$Hz, with the length $L_{pre} = L_w$, 90% and 78.5% one-shot success (Transmission of M succeeds with only one transmission) rate can be achieved in scenarios A and G. When $f_s = 40$Hz, 97.3% and 90.1% one-shot success rate can be achieved.

V. Discussions

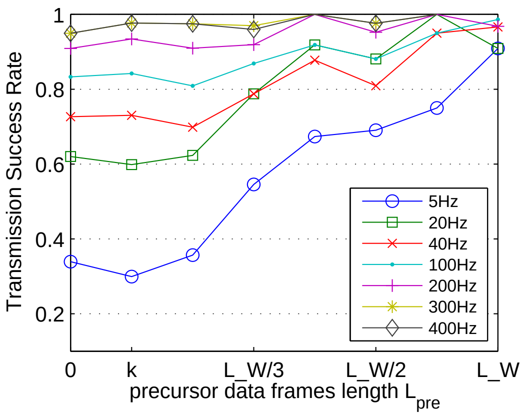
Driver Enhancement: In Intel IWL5300 NIC driver, there are some codes dealing with rate control for different situations. In our prototype, the rate control is modified to transmit the MFs using the same MCS rate of latest successful HT transmission. If it fails (no ACK reply), both precursor data frames and MF will be transmitted in the lowest MCS value in the "BasicMCSSet" to ensure the success delivery. We mention again that these modifications are permitted according to the "*Multirate Support*" in 802.11n Specification [27] Clause 9.6.

Source authentication for control frame: Theoretically, if CSI value could be obtained for control frame, similar source authentication could be applied to control frames. However, it is currently impossible to achieve this goal, since the ACK feedback mechanism is hard-coded in firmware which is a binary file compiled from closed-source code.

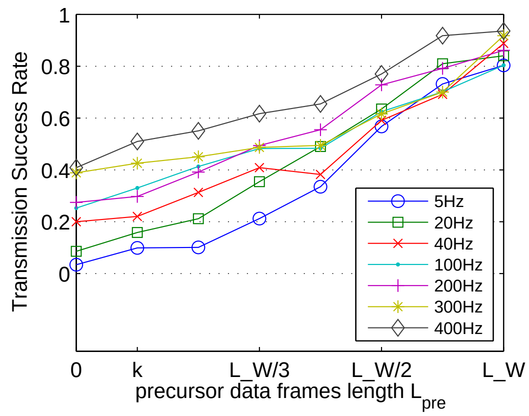
Vulnerability of Man-In-The-Middle Attack: Since CSITE detects spoofing MFs based on the CSI of encrypted data frames, if the data frames are replayed in physical layer, Man-In-The-Middle (MITM) attack may succeed. To launch MITM, the attacker must be able to jam the paired stations and simultaneously tunnel their traffic through the attacker. To detect such attacks, users only need to open a virtual monitor interface. If these is the jamming, the overheard flows to different address will disappear simultaneously, which is impossible in normal situation. This mitigates the impact of MITM attack. However, we believe in most of attack scenarios, such kind of powerful attacker does not exist.

VI. Conclusion

Management frame, the basis for operating 802.11 network normally, is extremely vulnerable to attacks. Spoofing detection without cooperative information is unreliable using existing methods. Based on off-the-shelf hardware, we design CSITE, a Wi-Fi management frame source authentication system. It leverages the unique characteristics of CSI to verify



(a) Successful Receiving Rate in A



(b) Successful Receiving Rate in G

the authenticity of MFs, and the detection is tuned to be highly strict for False Positive (FP) errors. To guarantee the successful delivery of MFs even under most intensive channel dynamics, we devise a method called CRE, which makes the MFs pass the detection with the help of precursor frames. Extensive evaluations are conducted to verify the performance of our system. These evaluations show excellent authentication ability and strong rejection against spoofing attacks.

Acknowledgement

This work was supported in part by the NSFC Major Program under Grant 61190110, the NSFC under Grants 61228202, 61033015 and 61170216, China 973 Program under Grant No.2011CB302705, NSF CNS-0832120, NSF CNS-1035894, NSF ECCS-1247944, and the Fundamental Research Funds for the Central Universities of China.

References

[1] J. Bellardo and S. Savage, "802.11 denial-of-service attacks: Real vulnerabilities and practical solutions," in *Proceedings of the USENIX Security Symposium*, 2003, pp. 15–28.

[2] H. Yang, J. Shu, X. Meng, and S. Lu, "Scan: self-organized network-layer security in mobile ad hoc networks," *Selected Areas in Communications, IEEE Journal on*, 2006.

[3] K. Pelechrinis, M. Iliofotou, and V. Krishnamurthy, "Denial of service attacks in wireless networks: The case of jammers," *IEEE Communications Surveys & Tutorials,*, 2010.

[4] W. Arbaugh, N. Shankar, Y. Wan, and K. Zhang, "Your 80211 wireless network has no clothes," *Wireless Communications, IEEE*, vol. 9, no. 6, pp. 44–51, 2002.

[5] M. Ahmad and S. Tadakamadla, "Short paper: security evaluation of ieee 802.11 w specification," in *Proceedings of the fourth ACM conference on Wireless network security*. ACM, 2011, pp. 53–58.

[6] M. Eian and S. F.Mjolsnes, "A formal analysis of ieee 802.11w deadlock vulnerabilities," in *IEEE INFOCOM'12*.

[7] Y. Sheng, K. Tan, and et al., "Detecting 802.11 mac layer spoofing using received signal strength," in *IEEE INFOCOM'08*.

[8] P. Chumchu, T. Saelim, and C. Sriklauy, "A new mac address spoofing detection algorithm using plcp header," in *IEEE ICOIN'11*.

[9] J. Yang, Y. Chen, W. Trappe, and J. Cheng, "Detection and localization of multiple spoofing attackers in wireless networks," 2012.

[10] C. Bo and Z. e. a. Jiang, "Locating sensors in the forest: A case study in greenorbs," in *IEEE INFOCOM'12*.

[11] W. Xi, Y. He, Y. Liu, J. Zhao, L. Mo, Z. Yang, J. Wang, and X. Li, "Locating sensors in the wild: pursuit of ranging quality," in *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*. ACM, 2010, pp. 295–308.

[12] Y. Liu, Z. Yang, X. Wang, and L. Jian, "Location, localization, and localizability," *Journal of Computer Science and Technology*, vol. 25, no. 2, pp. 274–297, 2010.

[13] C. Wu, Z. Yang, Y. Liu, and W. Xi, "Will: Wireless indoor localization without site survey," *IEEE Transactions on Parallel and Distributed Systems*, 2012.

[14] C. Mitchell, "Security analysis and improvements for ieee 802.11 i," in *(NDSS'05)*.

[15] M. Barbeau, J. Hall, and E. Kranakis, "Detecting impersonation attacks in future wireless and mobile networks," *Secure Mobile Ad-hoc Networks and Sensors*, pp. 80–95, 2006.

[16] B. Danev, H. Luecken, S. Capkun, and K. El Defrawy, "Attacks on physical-layer identification," in *ACM WiSec'06*.

[17] Y. Chen, W. Trappe, and R. Martin, "Detecting and localizing wireless spoofing attacks," in *Sensor, Mesh and Ad Hoc Communications and Networks, 2007. SECON'07. 4th Annual IEEE Communications Society Conference on*. IEEE, 2007, pp. 193–202.

[18] J. Yang, Y. Chen, W. Trappe, and J. Cheng, "Determining the number of attackers and localizing multiple adversaries in wireless spoofing attacks," in *IEEE INFOCOM'09*.

[19] K. Zeng, K. Govindan, D. Wu, and P. Mohapatra, "Identity-based attack detection in mobile wireless networks," in *IEEE INFOCOM'11*.

[20] N. Patwari and S. Kasera, "Robust location distinction using temporal link signatures," in *ACM Mobicom'07*.

[21] J. Zhang, M. Firooz, N. Patwari, and S. Kasera, "Advancing wireless link signatures for location distinction," in *ACM Mobicom'08*.

[22] S. Sen, R. Choudhury, and S. Nelakuditi, "Spinloc: Spin once to know your location."

[23] K. Wu, J. Xiao, Y. Yi, M. Gao, and L. Ni, "Fila: Fine-grained indoor localization," in *INFOCOM, 2012 Proceedings IEEE*. IEEE, 2012, pp. 2210–2218.

[24] S. Sen, B. Radunovic, R. Choudhury, and T. Minka, "Spot localization using phy layer information," in *ACM MobiSys'12*.

[25] Y. Liu and P. Ning, "Enhanced wireless channel authentication using time-synched link signature," in *IEEE INFOCOM'12*.

[26] T. Rappaport, "Wireless communications: principles and practice (2nd edition)," 2001.

[27] IEEE 802.11 n Working Group and others, IEEE Standard 802.11n.

[28] V. Hautamaki, I. Karkkainen, and P. Franti, "Outlier detection using k-nearest neighbour graph," in *IEEE ICPR'04*.

[29] C. Aggarwal and P. Yu, "Outlier detection for high dimensional data," *ACM Sigmod Record*, 2001.