On the Limitation of Embedding Cryptographic Signature for Primary Transmitter Authentication

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***Abstract*—Recently, an interesting primary transmitter authentication scheme was proposed. The main idea of this scheme is to have the primary transmitter embed cryptographic authentication tag at the physical layer. There are a number of features that make this scheme attractive. In this paper, we investigate the effective coverage areas for the primary and secondary receivers before and after applying this scheme. During the process, we reveal a serious limitation of this scheme, which may prohibit its application in practice.**

***Index Terms*—Wireless security, authentication, cognitive radio network.**

I. Introduction

A SERIOUS security threat to a cognitive radio (CR) network is the so-called Primary User Emulation (PUE) attack [1]. Under PUE attack, an adversary emulates the primary transmitter, and thus effectively shutting off potential opportunity for secondary users to access the spectrum. In the presence of PUE attack, spectrum sensing mechanisms based on either energy or feature detection are incapable of offering truthful results [3]. Thus, an effective primary transmitter authentication method is needed.

In [2], Liu *et al.* proposed an authentication scheme that integrates cryptographic and wireless link signatures. At the heart of this scheme is a "helper node", which is in close proximity to the primary transmitter. The helper node is assumed to share similar location-based channel impulse response (temporal link signature) to that of the primary transmitter. A secondary user first authenticates the helper node through its cryptographic signature. Then the secondary user is able to authenticate a primary user based on the temporal link signature that it receives from the helper node. A strong assumption of this scheme is that no attacker is allowed to be in close proximity to the primary transmitter. Another concern of this scheme is potential single point of failure at the helper node.

Very recently, Tan *et al.* [4] proposed an interesting authentication scheme that eliminates the need of a helper node as in [2]. A neat idea in their scheme is to have the primary transmitter embed cryptographic authentication tag at the physical layer through either modulation or channel coding (more details will be given in Section II). This information embedding process is equivalent to slightly perturbing the original signal purposely in a systematic manner. A secondary user will be able to extract the embedded authentication tags and perform primary transmitter authentication, while a primary receiver is expected to decode the slightly perturbed signal by treating the embedded additional information as noise.

For the ease of exposition, we abbreviate the scheme in [4] as ECS-PL (for Embedded Cryptographic Signature at the Physical Layer). At first glance, ECS-PL is appealing in a number of ways. First, ECS-PL is purely based on cryptographic signature, which is considered most effective in identifying PUE attack. Second, ECS-PL operates at the physical layer, and makes no requirement on upper layer compatibility between primary transmitters and secondary users for authentication. Such physical layer approach can support diverse population of secondary users under different upper layer protocols, as long as they understand physical layer signals. Third, it only requires a small modification of signal at the primary transmitter (i.e., TV tower). It does not require setting up any additional infrastructure such as the helper node in [2]. As a result, it eliminates any pitfalls associated with a helper node. Finally, it is *transparent* to primary receivers, in the sense that no hardware/software modification is needed at primary receivers. Existing primary receivers are still able to decode their received signals as the embedded tag information is treated as noise.

A performance analysis of ECS-PL focusing on user data error rate (for primary receivers) and authentication tag error rate (for secondary receivers) was given in [4]. In this paper, we investigate ECS-PL from a different perspective. We study the effective coverage areas for the primary receivers and secondary users under ECS-PL. Specifically, we focus on physical layer modulation based on QPSK (as in [4]) and investigate how to embed authentication tag bits without significant reduction in the coverage area for the primary receivers. That is, we will find the upper bound for the phase shift required to embed authentication tag bits in QPSK modulation so as to maintain a similar size of effective coverage area for primary receivers. Based on this upper bound, we find that the effective coverage area for the secondary receivers will be significantly reduced, rendering a large percentage of secondary users unable to perform authentication function, which violates the goal of ECS-PL scheme. Surprisingly, our finding is independent of some important system parameters such as primary transmitter power, bit rate, antenna heights and gains, and noise spectral density, among others.

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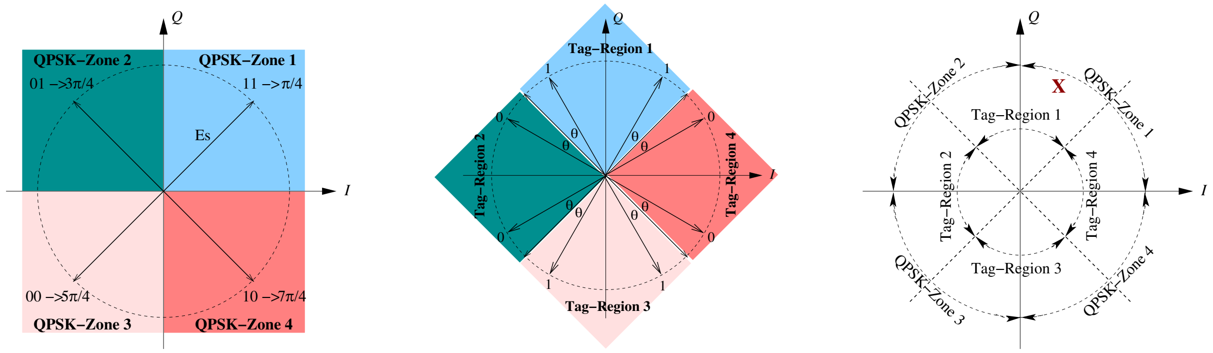

(a) QPSK-Zones (b) Tag-Regions (c) An example

Fig. 1: A schematic illustrating embedding cryptographic signature into QPSK modulation.

II. Embedding Cryptographic Signature into Physical Layer Modulation

The basic idea of ECS-PL is to embed the cryptographic authentication tag as noise into signal at the primary transmitter. Such embedded information may be considered as noise to a primary receiver. If such man-made noise is kept low enough, a primary receiver will be able to filter out such noise and recover the original transmitted signal. On the other hand, if such noise is above certain threshold, a secondary receiver (CR-based) will be able to extract the embedded cryptographic information from the received signal and use it to authenticate the primary transmitter. As discussed in [4], ECS-PL can be done either in modulation or channel coding and we focus on modulation in this letter. In the rest of this section, we briefly review ECS-PL with QPSK modulation.

QPSK Modulation of Signals. QPSK is a basic digital modulation technique that converts user data stream into transmitted signals (over a carrier frequency) with different phases. Specifically, user's digital data stream is broken into a sequence of two-bit pairs, with each pair being among the set of $\{11, 01, 00, 10\}$ possible pairs. Then QPSK maps each two-bit pair into one of the four phases on a QPSK constellation as shown in Fig. 1(a). Depending on which two-bit pair is used, a QPSK modulated carrier signal (over a symbol time interval T_s) can be represented by

$$S_i(t) = \sqrt{\frac{2E_s}{T_s}}\cos(2\pi f_c t + (2i-1)\frac{\pi}{4}) \qquad i = 1, 2, 3, 4,$$

where f_c is the carrier frequency and E_s is energy per symbol.

At receiver side, the received signal (which is the sum of original signal plus noise) will fall into one of the four zones of QPSK constellation. Depending on which zone the received signal falls into, a corresponding two-bit pair will be determined. Obviously, if the noise level is not too high, the received signal will fall into its expected zone with high probability.

Embedding Authentication Tags into Modulated Signals. The basic idea of embedding cryptographic information in a modulated signal is to perturb the pre-defined QPSK phases toward the horizontal I-axis or the vertical Q-axis by an "additional" small phase θ depending on the underlying tag bit (0 or 1). Specifically, in Fig. 1(b), for any of the four QPSK signals, if we want to embed a tag bit of 1 into the signal, we will shift an additional phase of θ toward the vertical Q-axis. Likewise, if we want to embed a tag bit of 0 into the signal, we will shift an additional phase of θ toward the horizontal I-axis. For decoding at the secondary receiver, we divide the 2π phase into four Tag-Regions, which is a $\pi/4$ counterclockwise phase shift of the four QPSK-Zones. Depending on which Tag-Region the received signal falls into, a secondary receiver will determine the corresponding tag bit. Note that after such phase perturbation, a transmitted signal will carry two pieces of information: the user data stream (a two-bit pair) and authentication tag information (one bit).

Recovering Signals and Authentication Tags at Primary and Secondary Receivers. For the modulated signal, additional noise will be added to the signal at a receiver. Depending on which QPSK-Zone the received signal falls into, a primary receiver will determine the corresponding user data (two-bit symbol). At the same time, depending on which Tag-Region the same received signal falls into, a secondary receiver will determine the corresponding tag information (one bit).

As an example, suppose a user data of 11 is being transmitted and a tag bit of 1 is to be embedded in the signal. Then the received signal is

$$\bar{S}(t, \theta) = \sqrt{\frac{2E_s}{T_s}}\cos(2\pi f_c t + \frac{\pi}{4} + \theta) + W(t),$$

where $W(t)$ is white Gaussian noise with zero mean and power spectral density $N_0/2$. Referring to Fig. 1(c), suppose the received signal falls at "X". Since this point is in QPSK-Zone 1, a primary receiver can determine the received user data being 11. At the same time, a secondary receiver can determine that the tag bit is 1 since the point is in Tag-Region 1. Clearly, θ is a critical parameter. We will show how to set θ in the next section.

III. Calculating Effective Coverage Areas

A comprehensive analysis of data and tag error probabilities for primary and secondary receivers was given in [4]. In this section, we focus on the impact of ECS-PL on the *effective coverage areas* for primary and secondary users, which was not explored in [4] but is vital to the successful application of this scheme in practice.

Procedure 1 Computing A_p

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Input: $p_t$, $h_t$, $G_t$, $h_r$, $G_r$, $P_s$, $L_0$, $N_0$ and $B_r$
Output: $R_p$, $A_p$
Compute $E_b$ based on (2);
Compute $p_r$ based on (3);
Compute $d$ based on (1);
return $R_p = d$, $A_p = \pi(R_p)^2$.
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Procedure 2 Computing $A_p^{\text{ECS-PL}}$

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Input: $p_t$, $h_t$, $G_t$, $h_r$, $G_r$, $P_s$, $L_0$, $N_0$, $B_r$ and $\theta$
Output: $R_p^{\text{ECS-PL}}$, $A_p^{\text{ECS-PL}}$
Compute $E_b$ based on (4);
Compute $p_r$ based on (3);
Compute $d$ based on (1);
return $R_p^{\text{ECS-PL}} = d$, $A_p^{\text{ECS-PL}} = \pi(R_p^{\text{ECS-PL}})^2$.
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We assume the signal propagation between a primary transmitter (e.g., TV tower) and a receiver (either primary or secondary) follows a two-ray model (attenuation over reflecting surface) [5, Chapter 3], i.e.,

$$p_r = \left[\frac{h_t h_r}{d^2}\right]^2 \frac{(G_t G_r)}{L_0} p_t, \tag{1}$$

where p_t, h_t and G_t are the signal power, antenna height and gain of the primary transmitter, p_r, h_r and G_r are the signal power, antenna height and gain of a receiver; d is the distance between the transmitter and receiver, and L_0 is a parameter for other losses expressed as a relative attenuation factor.

(i) Effective Coverage Area for Primary Receivers before ECS-PL We first calculate the effective coverage area of the primary transmitter before ECS-PL scheme is employed. Denote this area as A_p and its radius (transmission range) as R_p. Denote P_s as the symbol error rate at a primary receiver. Then we have [5, Chapter 9]

$$P_s \simeq \text{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right), \tag{2}$$

where erfc is the complimentary error function, E_b/N_0 is energy per bit to noise power spectral density ratio at a receiver. So once we have a target P_s for a given N_0, we can obtain energy per bit E_b. Once we have E_b, we can calculate the received signal power as

$$p_r = E_b B_r, \tag{3}$$

where B_r is the bit rate. With p_r and (1), we can obtain d, which is also R_p. We summarize the above steps in Procedure 1.

(ii) Effective Coverage Area for Primary Receivers after ECS-PL After ECS-PL is employed, signal symbol error rate is given by [4]:

$$P_s \simeq \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_b}{N_0}}(\cos\theta - \sin\theta)\right) + \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_b}{N_0}}(\cos\theta + \sin\theta)\right), \tag{4}$$

where θ is the phase shifting angle for embedding authentication tags. By the same token in Procedure 1, we can compute the effective transmission range (denoted as $R_p^{\text{ECS-PL}}$) as well as the coverage area (denoted as $A_p^{\text{ECS-PL}}$) for primary receivers after ECS-PL is employed. We summarize the steps in Procedure 2.

Procedure 3 Computing $A_s^{\text{ECS-PL}}$

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Input: $p_t$, $h_t$, $G_t$, $h_r$, $G_r$, $P_s$, $L_0$, $N_0$, $B_r$, $\theta$, $P_e^{\text{tag}}$, BCH($n^{\text{tag}}$,$k^{\text{tag}}$, $t^{\text{tag}}$) and $L$
Output: $R_s^{\text{ECS-PL}}$, $A_s^{\text{ECS-PL}}$
Compute $P_{cw}^{\text{tag}}$ based on (7);
Compute $P_t$ based on (6);
Compute $E_b$ based on (5);
Compute $p_r$ based on (3);
Compute $d$ based on (1);
return $R_s^{\text{ECS-PL}} = d$, $A_s^{\text{ECS-PL}} = \pi(R_s^{\text{ECS-PL}})^2$.
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(iii) Effective Coverage Area for Secondary Receivers after ECS-PL After ECS-PL is employed, secondary receivers will receive the same signal as primary users but are only interested in decoding the tag information for authentication. The tag bit error rate, denoted as P_t, is given by [4]:

$$P_t \simeq \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_b}{N_0}}(\cos\theta)\right) + \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_b}{N_0}}(\sin\theta)\right). \tag{5}$$

Even more important than P_t is the tag error rate, denoted as P_e^{tag}, which is defined as the probability of having one or more bits in error in the L-bit authentication tag and should be kept extremely low, e.g., below 10^{-10} [4]. Such stringent requirement is due to the fact that an authentication tag (with L bits) is a cryptographic hash value, which cannot tolerate even a single bit error. To keep P_e^{tag} low, error correcting codes (ECC) can be used. First, a L-bit authentication tag is broken up into a number of k^{tag}-bit segments. Under ECC, each k^{tag}-bit segment is encoded into n^{tag}-bit codeword, which can correct up to t^{tag}-bit errors. Denote P_{cw}^{tag} as the probability that the received n^{tag}-bit codeword is in error. Then P_{cw}^{tag} is upper bounded by [6, Chapter 3]:

$$P_{cw}^{\text{tag}} \le \sum_{i=t^{\text{tag}}+1}^{n^{\text{tag}}} \binom{n^{\text{tag}}}{i} P_t^i (1-P_t)^{n^{\text{tag}}-i}, \tag{6}$$

where P_t is the tag bit error rate in (5). With P_{cw}^{tag}, P_e^{tag} can be further bounded by [4]:

$$P_e^{\text{tag}} \le 1 - (1 - P_{cw}^{\text{tag}})^{\frac{L}{k^{\text{tag}}}}. \tag{7}$$

So to achieve P_e^{tag} on the tag information, we can calculate the maximum P_{cw}^{tag} from (7). With this P_{cw}^{tag}, we can calculate P_t in (6). Then, we can follow the same token as in Procedure 1 to obtain the effective transmission range (denoted as $R_s^{\text{ECS-PL}}$) and coverage area (denoted as $A_s^{\text{ECS-PL}}$) for secondary receivers. We summarize the steps in Procedure 3.

Guideline for Setting θ — Putting Everything Together For a given θ (see Fig. 1(b)), it is not hard to see that $A_p^{\text{ECS-PL}}$ will be smaller than A_p under the same settings for other parameters.[1] This is intuitive as the perturbation on the QPSK

[1] We assume that the transmission power for the primary transmitter cannot be increased per FCC requirement.

TABLE I: Results for $(1 - \frac{A_s^{\text{ECS-PL}}}{A_p})$ and θ under different BCH codes and P_s with $A_p^{\text{ECS-PL}} = 0.95 \cdot A_p$.

BCH code, P_s	θ	$(1 - \frac{A_s^{\text{ECS-PL}}}{A_p})$
$(127, 50, 13)$, 2×10^{-3}	$\frac{\pi}{32}$	87.07%
$(127, 50, 13)$, 2×10^{-4}	$\frac{\pi}{37}$	86.53%
$(127, 50, 13)$, 2×10^{-5}	$\frac{\pi}{41}$	86.06%
$(511, 10, 127)$, 2×10^{-3}	$\frac{\pi}{32}$	72.31%
$(511, 10, 127)$, 2×10^{-4}	$\frac{\pi}{37}$	71.17%
$(511, 10, 127)$, 2×10^{-5}	$\frac{\pi}{41}$	70.15%
$(1023, 11, 255)$, 2×10^{-3}	$\frac{\pi}{32}$	68.71%
$(1023, 11, 255)$, 2×10^{-4}	$\frac{\pi}{37}$	67.42%
$(1023, 11, 255)$, 2×10^{-5}	$\frac{\pi}{41}$	66.28%

constellation (to embed authentication tag) is considered additional noise by a primary receiver. But to comply with FCC requirements, the impact of ECS-PL on $A_p^{\text{ECS-PL}}$ should be minimal, meaning that $A_p^{\text{ECS-PL}}$ should be comparable to A_p, e.g., $A_p^{\text{ECS-PL}} \geq 0.95 \cdot A_p$ or even higher. Such requirement offers a guideline on how to set θ.

Once we have determined θ, we investigate $A_s^{\text{ECS-PL}}$ in relative to A_p in the next section.

IV. Main Result

In this section, we investigate $A_s^{\text{ECS-PL}}$ in relative to A_p. The guideline on how to set θ was discussed in the last section. Specifically, based on Procedure 1, we can calculate A_p. Then by setting $A_p^{\text{ECS-PL}} = 0.95 \cdot A_p$, we can use Procedure 2 in a reverse manner to calculate θ. Based on this θ, we can use Procedure 3 to calculate $A_s^{\text{ECS-PL}}$.

Since we are interested in finding how much smaller of $A_s^{\text{ECS-PL}}$ in relative to A_p, we calculate $(1 - A_s^{\text{ECS-PL}}/A_p)$. Interestingly, this calculation is independent of the settings for parameters p_t, h_t, G_t, h_r, G_r, L_0, N_0 and B_r, as they show up both on the numerator and denominator and cancel out. To generate authentication tag, we assume SHA-1 is used (with a length of 160 bits). The only remaining parameters that need to be set are data symbol error rate P_s, authentication tag error rate P_e^{tag}, and BCH code for ECC.

- P_s: We will consider three bit error rates that a primary receiver can tolerate: 10^{-3}, 10^{-4} and 10^{-5}. These correspond to approximately 2×10^{-3}, 2×10^{-4}, and 2×10^{-5} for symbol error rate P_s, respectively, due to QPSK.
- P_e^{tag} is set to 10^{-10}, same as that in [4].
- BCH code: We tried all primitive BCH codes available in [6, Appendix C] and the results are consistent. For illustration, we show our results for three sets of BCH codes in the form of (n^{tag}, k^{tag}, t^{tag}) in Table I. The first set of code $(127, 50, 13)$ was used in [4]. The codes $(511, 10, 127)$ and $(1023, 11, 255)$ are not commonly used but are extremely powerful. They are chosen to represent extreme BCH codes in our study.

Table I shows our numerical results. We find that for all cases, θ is quite small and $(1 - A_s^{\text{ECS-PL}}/A_p)$ is quite high, showing a significant reduction of effective area for secondary receivers. Assuming uniform secondary user density in the area, this means that *there is a very large percentage (over* 65%*) of secondary users unable to perform primary transmitter authentication.* Although more powerful BCH codes help reduce $(1 - A_s^{\text{ECS-PL}}/A_p)$ (from 86% to 67% for $P_s = 2 \times 10^{-4}$), there is hardly much further improvement one can expect as we have exhausted all public available BCH codes.

It is worth pointing out that if FCC requires more stringent area coverage for $A_p^{\text{ECS-PL}}$, e.g., $A_p^{\text{ECS-PL}} = 0.99 \cdot A_p$, then $(1 - A_s^{\text{ECS-PL}}/A_p)$ will become even worse (an increase). For example, under BCH code (127, 50, 13) and $P_s = 2 \times 10^{-3}$, $(1 - A_s^{\text{ECS-PL}}/A_p)$ increases to 95% when $A_p^{\text{ECS-PL}} = 0.99 \cdot A_p$, meaning that 95% of secondary receivers are not able to authenticate the primary transmitter.

The large reduction of $A_s^{\text{ECS-PL}}$ in our findings can be explained by the very small value of θ one can choose in order to ensure $A_p^{\text{ECS-PL}}$ is comparable to A_p. This will result in large tag bit error rate P_t as well as tag error rate P_e^{tag} (even with ECC). On the other hand, there is a very high requirement on P_e^{tag} (e.g., 10^{-10}) as a single bit error in an authentication tag will render its useless. Under such environment, only a small percentage of secondary users that are very close to the primary transmitter will have adequate received signal power and decode the authentication tag correctly.

V. Conclusion

In this paper, we investigated a recently proposed primary transmitter authentication scheme that embeds cryptographic authentication information at the physical layer. We focused on the effective coverage areas for primary and secondary receivers under this scheme. We found that by requiring a similar size of coverage area for primary receivers before and after the scheme, the effective coverage area for secondary users must be much smaller than that for primary users. Consequently, a large percentage of secondary users are not able to decode the cryptographic signature for authentication. Interestingly, our finding is independent of some important system parameters such as primary transmitter power, signal bit rate, antenna heights and gains, and noise spectral density. Our findings show a fundamental limitation of the proposed physical layer authentication scheme and thus encourage further research in this important area.

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