

# Securing Cognitive Radio Networks against Primary User Emulation Attacks

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**Abstract**—Cognitive Radio (CR) is a promising technology for next-generation wireless networks in order to efficiently utilize the limited spectrum resources and satisfy the rapidly increasing demand for wireless applications and services. Security is a very important but not well addressed issue in CR networks. In this paper we focus on security problems arising from Primary User Emulation (PUE) attacks in CR networks. We present a comprehensive introduction to PUE attacks, from the attacking rationale and its impact on CR networks, to detection and defense approaches. In order to secure CR networks against PUE attacks, a two-level database-assisted detection approach is proposed to detect such attacks. Energy detection and location verification are combined for fast and reliable detection. An admission control based defense approach is proposed to mitigate the performance degradation of a CR network under a PUE attack. Illustrative results are presented to demonstrate the effectiveness of the proposed detection and defense approaches.

**Index Terms**—Cognitive radio, security, primary user emulation attack, energy detection, location verification.

## I. INTRODUCTION

Cognitive Radio (CR) is an enabling technology to effectively address the spectrum scarcity and it will significantly enhance the spectrum utilization of future wireless communications systems. In a CR network, the Secondary (or unlicensed) User (SU) is allowed to opportunistically access the spectrum “holes” that are not occupied by the Primary (or licensed) User (PU). Generally, the SUs constantly observe the spectrum bands by performing spectrum sensing. Once a spectrum “hole” is discovered, an SU could temporarily transmit on this part of the spectrum. Upon the presence of a PU in this part of the spectrum, however, the SU has to switch to another available spectrum band by performing spectrum handoff, avoiding interference with the PU transmission. The development of CR technology leads to the new communications paradigm called Dynamic Spectrum Access (DSA), which relaxes the traditional fixed spectrum assignment policy and allows a CR networks to temporarily “borrow” a part of the spectrum from the primary network. As a consequence, the scarce spectrum resources are shared, in a highly efficient

and resilient fashion, between the primary network and the CR network.

Among all the key technical problems of CR networks, security is a crucial but not well addressed issue. Due to the nature of dynamic spectrum access and the fact that the CR network should not interact with the primary network, the SUs in the CR network usually lack global information about the usage of the spectrum resource in the network. This makes the CR network vulnerable to attacks by hostile users. In all the main functionalities of CR networks such as spectrum sensing, spectrum mobility, spectrum sharing and spectrum management, the CR network has been shown to be strategically vulnerable [1]. The typical attacks on CR networks may include Denial of Service (DoS) attacks, system penetration, repudiation, spoofing, authorization violation, malware infection, and data modification. These attacks cause potential threats to the information confidentiality, integrity and availability of the CR network. Effective defense approaches are urgently needed to secure CR networks and deal with these attacks. Nowadays, security threats and their countermeasures have been studied as one of the most important topics in the research area of CR technology [6].

In this paper, we mainly focus on the security problem arising from Primary User Emulation (PUE) attacks in CR networks. PUE attacks are known as a new type of attacks unique to CR networks. In such an attack, the hostile user takes the advantage of the inherent etiquette in CR networks that the legitimate SU has to evacuate the spectrum band upon the arrival of a PU. An attacker emulates the PU’s transmitting signal and misleads the legitimate SU to give up the spectrum band. The presence of PUE attacks may severely influence the performance of CR networks. This paper aims at presenting a comprehensive introduction to PUE attacks, from the attacking principle and its impact on CR networks, to the detection and defense approaches. In order to secure CR networks, we propose a database-assisted detection approach and an admission control based defense approach against PUE attacks.

The remainder of the paper is organized as follows. Section II illustrates the principles of PUE attacks, and introduces its classification and impacts on CR networks. A quantitative analysis of the performance degradation of a CR network due to a PUE attack is also presented. Section III describes existing detection measures for PUE attacks. A two-level database-assisted detection approach is proposed. Energy detection and location verification are combined for both fast and reliable detection. Section VI discusses the defense approaches against

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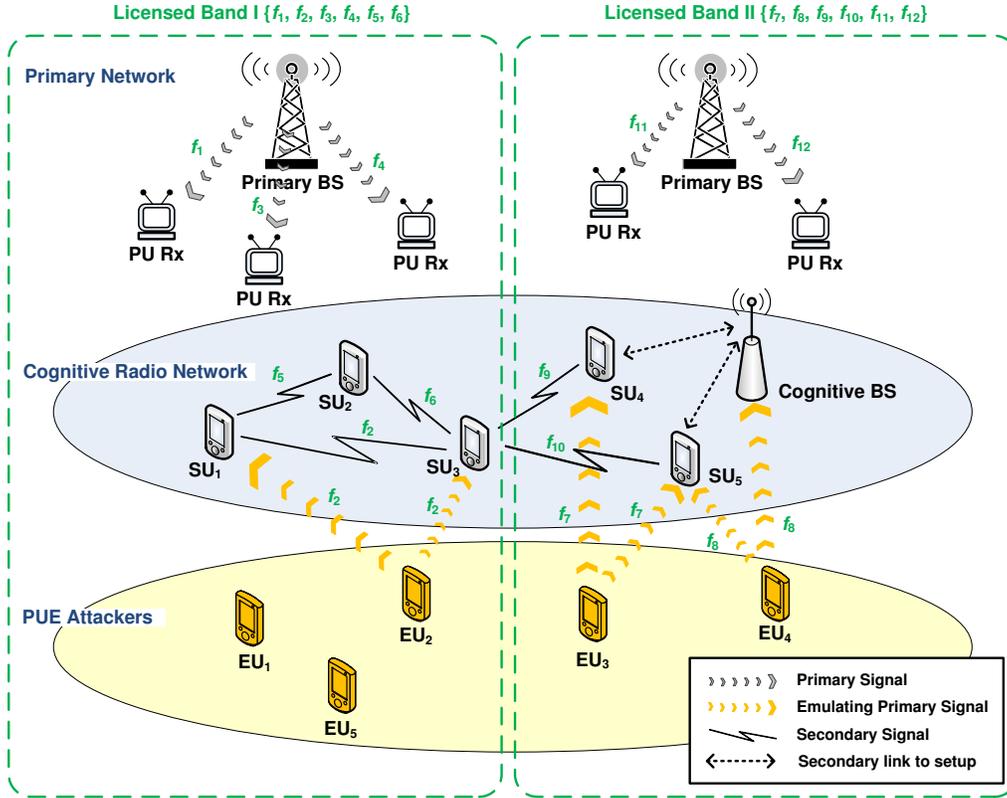


Fig. 1. Illustration of PUE attacks in the CR network.

PUE attacks, where a guard channel based admission control is adopted to defend against PUE attacks. Finally, the conclusions of the paper are presented in Section V.

## II. PUE ATTACK AND ITS IMPACT ON CR NETWORKS

The term Primary User Emulation (PUE) attack was first introduced in [2]. A PUE attack is a new type of attack unique to CR networks, in which the attackers may modify their radio transmission frequency to mimic a primary signal, thereby misguiding the legitimate SUs to erroneously identify the attackers as a PU.

Fig. 1 shows a typical scenario of a PUE attack. There are two spectrum bands, say, licensed band I and band II. Both of the spectrum bands have six channels, indexed by frequencies  $f_1, f_2, \dots, f_6$ , and  $f_7, f_8, \dots, f_{12}$ , respectively. Let's consider the first example in band I, where the primary base station (BS) is transmitting in channels  $f_1, f_3$  and  $f_4$  to the PU receivers. Channels  $f_2, f_5$  and  $f_6$  are idle. By observing this,  $SU_1, SU_2$  and  $SU_3$  are allowed to use these three idle channels for transmissions. However, the appearance of a PUE attacker, say,  $EU_2$ , may block the SUs from using an idle channel.  $EU_2$ , may, for example, mimic the primary signal in channel  $f_2$ . Once the attack succeeds,  $SU_1$  and  $SU_3$  are misled to evacuate channel  $f_2$  and the link between them is interrupted. The second example is shown in band II. The primary network is occupying channels  $f_{11}$  and  $f_{12}$ , while  $SU_4$  and  $SU_5$  are using channels  $f_9$  and  $f_{10}$ , respectively. PUE attackers  $EU_3$  and  $EU_4$  are emulating the primary signals in channels  $f_7$  and

$f_8$ , respectively. In this situation, suppose that  $SU_4$  and  $SU_5$  need to find channels to connect with the cognitive base station (BS). If attackers  $EU_3$  and  $EU_4$  can not be correctly identified,  $SU_4$  and  $SU_5$  will find no vacant channels and hence may not be able to communicate with the cognitive BS.

The above two examples describe two different attacking cases. The first example illustrates the case that the PUE attacker attacks the in-service SUs and seizes one of their channels, causing interruption of some of the SU services. The second example illustrates the case that the PUE attackers occupy the idle channels and waste the spectrum opportunities of the SUs.

### A. Classification of Attackers

Since the security problem caused by PUE attacks was identified, different types of PUE attacks have been studied. We now introduce different types of PUE attackers associated with their classification criteria.

- *Selfish & Malicious Attackers*: A selfish attacker aims at stealing bandwidth from legitimate SUs for its own transmissions. The attacker will monitor the spectrum. Once an unoccupied spectrum band is discovered, it will compete with the legitimate SUs by emulating the primary signal, e.g.,  $SU_3$  and  $SU_4$  in Fig. 1. A selfish attacker is a rational attacker in the sense that, if it is detected by the legitimate SUs and the SUs reclaim the spectrum opportunity by switching back to the band, it

has to leave the band. The purpose of a malicious attacker, however, is to disturb the dynamic spectrum access of legitimate SUs but not to exploit the spectrum for its own transmissions. Being different from a selfish attacker, the malicious attacker may emulate a primary signal in both an unoccupied spectrum band and a band currently used by legitimate SUs, e.g.,  $SU_2$  in Fig. 1. When an attacker attacks a band being used by a legitimate SU, there exists the possibility that the SU fails to discover the signal, and hence, an interference occurs between the attacker and the legitimate SU.

- *Power-Fixed & Power-Adaptive Attackers:* The ability to emulate the power levels of a primary signal is crucial for PUE attackers, because most of the SUs employ an energy detection technique in spectrum sensing. A power-fixed attacker uses an invariable predefined power level regardless of the actual transmitting power of the PUs and the surrounding radio environment. Compared to the power fixed attacker, the power-adaptive attacker is smarter in the sense that, it could adjust its transmitting power according to the estimated transmitting power of the primary signal and the channel parameters [3]. Specifically, the attacker employs an estimation technique and a learning method against the detection by the legitimate SUs. It is demonstrated that such an advanced attack can defeat a naive defense approach that focuses only on the received signal power.
- *Static & Mobile Attackers:* The location of a signal source is also a key characteristic to verify the identity of an attacker. A static attacker has a fixed location that would not change in all round of attacks. By using positioning techniques such as Time of Arrival (ToA) or dedicated positioning sensors [8], the location of a static attacker could be revealed. A static attacker will be easily recognized due to the difference between its location and that of the PUs. A mobile attacker will constantly change its location so that it is difficult to trace and discover. A viable detection approach that exploits the correlations between RF signals and acoustic information is proposed in [4] to verify the existence of a mobile PUE attacker.

### B. Essential Conditions for Successful PUE Attacks

In a CR network, the successful realization of a PUE attack relies on several essential conditions. To better understand PUE attacks and facilitate the design of the countermeasures, we summarize these essential conditions as follows.

- *No PU-SU interaction:* There is no interaction between the primary and the secondary networks. This is a necessary condition for a successful PUE attack. Otherwise, if the legitimate SUs are allowed to exchange information with the PUs, a PU verification procedure could be designed to easily detect a PUE attack. In most cases, this condition holds. It is regulated in the IEEE 802.22 standard and also a general assumption in most existing research work of CR networks.
- *PU and SU signals have different characteristics:* The primary and secondary networks use wireless signals with

different characteristics, i.e., using different modulation modes and different signal statistical features. An SU receiver is inherently designed only for the secondary signal but unable to demodulate and decode the primary signal. The PUE attackers take advantage of this fundamental condition to emulate the primary signal that is unrecognisable for the legitimate SUs.

- *Primary signal learning and channel measurement:* To emulate the primary signal, the attacker has to track and learn the characteristics of the primary signal. For an advanced attack, the attacker may also estimate the power level as well as the channel conditions to generate more tricky transmitting signals.
- *Avoiding interference with the primary network:* Although this is usually a primary concern for the SUs, it is also an important condition that the PUE attackers have to comply with. The attackers, especially the selfish ones, should carefully monitor the behaviors of PUs as not to cause extra interference with the primary network.

### C. Impact of PUE attacks on CR Networks

The presence of PUE attacks causes a number of troublesome problems for CR networks. The list of potential consequences of PUE attacks is:

- *Bandwidth waste:* The ultimate objective of deploying CR networks is to address the spectrum under-utilization that is caused by the current fixed spectrum usage policy. By dynamically accessing the spectrum “holes”, the SUs are able to retrieve these otherwise wasted spectrum resources. However, PUE attackers may steal the spectrum “holes” from the SUs, leading to spectrum bandwidth waste again.
- *QoS degradation:* The appearance of a PUE attack may severely degrade the Quality-of-Service (QoS) of the CR network by destroying the continuity of secondary services. For instance, a malicious attacker could disturb the ongoing services and force the SUs to constantly change their operating spectrum bands. Frequent spectrum handoff will induce unsatisfying delay [7] and jitter for the secondary services.
- *Connection unreliability:* If a realtime secondary service is attacked by a PUE attacker and finds no available channel when performing spectrum handoff, the service has to be dropped. This realtime service is then terminated due to the PUE attack. In principle, the secondary services in CR networks inherently have no guarantee that they will have stable radio resource because of the nature of dynamic spectrum access. The existence of PUE attacks significantly increases the connection unreliability of CR networks.
- *Denial of Service:* Consider PUE attacks with high attacking frequency; then the attackers may occupy many of the spectrum opportunities. The SUs will have insufficient bandwidth for their transmissions, and hence, some of the SU services will be interrupted. In the worst case, the CR network may even find no channels to set up a common control channel for delivering the control messages. As

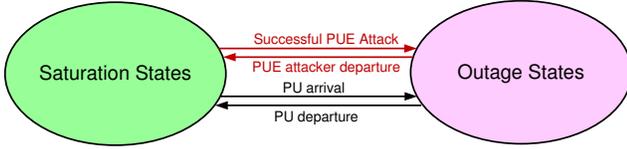


Fig. 2. Saturation state and outage state transition.

a consequence, the CR network will be suspended and unable to serve any SU. This is called Denial of Service (DoS) in CR networks.

- *Interference with the primary network:* Although a PUE attacker is motivated to steal the bandwidth from the SUs, there exists the chance that the attacker generates additional interference with the primary network. This happens when the attacker fails to detect the occurrence of a PU. On the other hand, when the SUs are tackling a PUE attack, it is also possible to incorrectly identify the true PU as the attacker and interfere with the primary network. In any case, causing interference with the primary network is strictly forbidden in CR networks.

#### D. Performance Degradation due to PUE Attacks

We adopt the term *saturation* to characterize the state of a CR network in which all the channels are occupied by PUs, SUs and PUE attackers, i.e., there are no idle channels, and the term *outage* to characterize the state of a CR network in which there is no spectrum band available for the Common Control Channel (CCC). In a practical CR network, it is necessary to build up a CCC for exchanging control messages. The CCC might be established by using a dedicated radio transceiver and setting up an out-of-band fixed channel. However, this is very difficult in a real CR network due to the additional cost of hardware and the assignment of a dedicated spectrum band. It is more likely that the CCC should be constructed by means of dynamic spectrum access. This implies that the CR network need to maintain a stable channel as its CCC. Under PUE attacks, the CCC may also be attacked and disconnected. The system will be suspended in this case. Two new performance metrics are defined as follows.

- *Outage probability:* The outage probability is defined as the probability that a CR network stays in the outage state in which there is no available spectrum band for constructing a CCC.
- *System recovery time:* The system recovery time is defined as the average time duration that a CR network (in the outage state) takes to acquire an available spectrum band as a CCC for delivering control messages.

Fig. 2 shows the saturation state and the outage state transition. When the current CCC is not available any more, due to the arrival of a PU or a PUE attack, it has to switch to a new channel. Since the CCC has priority over the other common SUs, it could switch to anyone of the available channels, even one already occupied by the SUs. As a consequence, the CCC is disconnected only in the case that all of the channels are occupied by PUs or PUE attackers. In the saturation states with

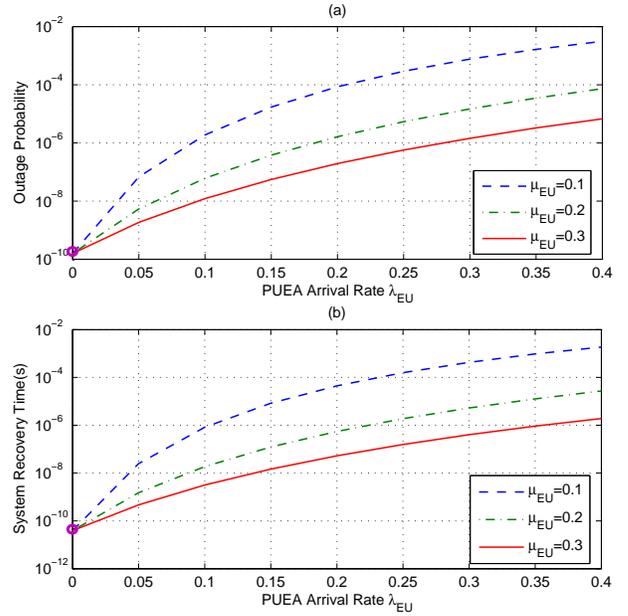


Fig. 3. Outage probability and system recovery time.

only one SU channel being used as the CCC, if a PU arrives and occupies the CCC, or if a PUE attacker successfully attacks the CCC, the CR network transits to the outage state.

Fig. 3 shows the outage probability and the system recovery time in terms of the PUE attacking strength, i.e., the attack arrival rate. In the figure,  $\lambda_{EU}$  and  $\mu_{EU}$  denote the PUE attacker arrival rates and the PUE attacker departure rate, respectively. It is observed that, both the outage probability and the system recovery time increase dramatically with the increase of the attacking strength. Without PUE attacks, the outage probability is near zero and the recovery time is very short. In the case of a PUE attack, say,  $\lambda_{EU} = 0.4$  and  $\mu_{EU} = 0.1$ , the outage probability is over 0.3% and the recovery time is nearly 2ms. Hence, the outage probability increases dramatically, and the recovery time extend substantially, compared to the case when there are no PUE attacks. These observations indicate that, the existence of PUE attacks may seriously degrade the performance of a CR network. Detection and defense approaches against PUE attacks are becoming very critical to secure CR networks.

### III. DETECTION APPROACHES FOR PUE ATTACKS

#### A. Existing Detection Approaches

In the literature, some detection approaches against PUE attacks have been presented. The existing detection approaches can be classified into energy detection, Received Signal Strength (RSS) based detection, feature detection, location verification and cooperative detection.

1) *Energy Detection:* Energy detection is a simple but widely used approach for spectrum sensing in CR networks. It is also one of the basic approaches for the detection of PUE attacks. By measuring the power level of the received signal at the SU receiver and comparing it with that from the true PUs, the CR network could judge whether the signal comes

from an attacker or not. However, a pure energy detector is not robust enough to tackle an advanced PUE attack.

2) *RSS-based Detection*: Received Signal Strength (RSS) based detection approach is discussed in [5], where the authors analyze the PUE attack in the CR network without using any location information. Thus, this detection approach does not need dedicated sensor networks. The PUE attackers are assumed to be distributed randomly around the SUs. The authors present an analysis using Fentons approximation and Walds sequential probability ratio test (WSPRT) to detect PUE attacks.

3) *Feature Detection*: The approach proposed in [9] uses energy detection to identify the existing users in the frequency band. The approach then employs a cyclostationary calculation to represent the features of the user signals, which are then fed into an artificial neural network for classification. As opposed to current techniques for detecting PUE attacks in CR networks, this approach does not require additional hardware or time synchronization algorithms in the wireless network.

4) *Location Verification*: Two location verification schemes are proposed in [2]. They are called Distance Ratio Test (DRT) and Distance Difference Test (DDT), respectively. In both schemes, dedicated cognitive nodes (SUs or a cognitive BS) with enhanced functionality are involved for location verification. DRT uses a Received Signal Strength (RSS) based method, where two dedicated cognitive nodes measure the RSS of the signal source and calculate the ratio of these two RSS to check whether it coincides with their distances to the true PU (e.g., a TV broadcast tower). Using DDT, the arrival time of the transmitted signal from the source is measured by the two dedicated cognitive nodes. The product of the time difference and the light speed is then compared to the distance difference from the true PU to the two dedicated nodes in order to identify the source.

### B. A Database-Assisted Detection Approach

Fig. 4 shows our proposed database-assisted PUE attack detection approach, which has three key components: the multi-threshold fast energy detection, the fingerprint-based location verification and the two-level database. In the approach, a local database is integrated in each SU, while a global database is built up in the cognitive BS. The local database is used to store historical spectrum sensing data and the local detection decisions of each SU. The global database is used to collect and record all the SUs' spectrum sensing data and the local detection decisions, as well as the global detection decisions. If the proposed approach is applied in wireless regional area networks, according to the IEEE 802.22 standard [10], the global database in a cognitive BS can provide an interface to the incumbent database for information query, e.g., the geo-location of a primary BS and the list of available channels. The main operations of the proposed detection approach are explained as follows.

1) *Basic Operations*: We consider a system model in which there are one primary BS (e.g., the TV broadcasting tower) and multiple PUE attackers. In our model the attackers are static or quasi-static, say, moving very slowly. In a given moment

and in a specific spectrum band (channel), only one of the attackers, at most, will emulate a primary signal.

In the proposed approach, there are four main units in the SU: a signal pre-processing unit, a fast energy detector, a location verifier and a local database. The local database consists of two components: An RSS Probability Density Function (PDF) database and a fingerprint database. The signal pre-processing unit gets the received signal  $r(t)$  from the radio frequency (RF) unit as input. Let  $x(t)$ ,  $h(t)$  and  $\omega(t)$  denote the transmitted signal, channel impulse response and the receiver thermal noise, respectively. Let  $s(t)$  and  $s'(t)$  denote the real PU signal and the PUE attack signal, respectively. Then, the transmitted signal  $x(t) = s(t)$  for the real PU signal,  $x(t) = s'(t)$  for the PUE attack signal, and  $x(t) = 0$  when no signal is transmitted. The input signal is given by  $r(t) = x(t)*h(t)+\omega(t)$ . Let  $\{t_n\}$  denote the sequence of sampling times and  $N_s$  the number of samples in one sensing period. After sampling, squaring and aggregation, the signal pre-processing unit generates the sampled energy vector  $\mathbf{e} = e[n]$  ( $n = 1, 2, \dots, N_s$ ) and the aggregated energy  $E$ . Then, we have the sampled energy  $e[n] = r^2(t_n)$  and the aggregated energy  $E = \sum_1^{N_s} e[n]$ . After that, the aggregated energy  $E$  is sent to the fast energy detector for comparison to the preset thresholds  $\gamma_k$ 's. If the comparison result indicates that there is no signal or it is a PUE attack signal, the detection procedure is terminated and the corresponding decision is made. Otherwise, the energy vector  $e[n]$ , containing more detailed energy information, is sent to the location verification unit. The location of the source of the signal is estimated using Bayesian hypothesis testing. The estimated location  $\hat{m}$  of the signal source is then transmitted to the cognitive BS for data fusion. The operations of fast energy detector and location verifier are elaborated below.

2) *Multiple Thresholds based Fast Energy Detection*: The goal of a fast energy detector is to quickly react to possible PUE attacks. The basic idea of a fast energy detector stems from conventional energy detection. In a conventional energy detector, there is only one energy threshold, to distinguish the cases of presence or absence of a primary signal. This single-threshold detector is not efficient for detecting a PUE attack signal. To distinguish a PUE attacker from a real PU, a fast energy detector sets up three energy thresholds, denoted by  $\gamma_0, \gamma_1$  and  $\gamma_2$ . Here,  $\gamma_0 < \gamma_1 < \gamma_2$ , and  $\gamma_0$  is according to the original threshold in a conventional energy detector. If the input  $E < \gamma_0$ , it is decided that there is no PU or PUE attacker present. The two new thresholds  $\gamma_1$  and  $\gamma_2$  are used to distinguish the signals of PU and PUE attacker. If the input  $\gamma_0 < E < \gamma_1$  or  $E > \gamma_2$ , it is decided that a PUE attack is detected. Otherwise, the received signal is initially diagnosed to be a PU signal. The location verifier will be launched for further examination. It is emphasized that, using two energy thresholds to distinguish a PU from a PUE attacker is justified by the following fact. A PUE attacker tries to emulate the transmitting power of a real PU. However, it is very difficult for the attacker to fabricate a signal so that all of the SUs receive the signal with the power level similar to that of the real PU. By randomly assigning a few SUs to measure the received signal power, and letting these SUs know the signal power of the real PUs, a PUE attack could be discovered with

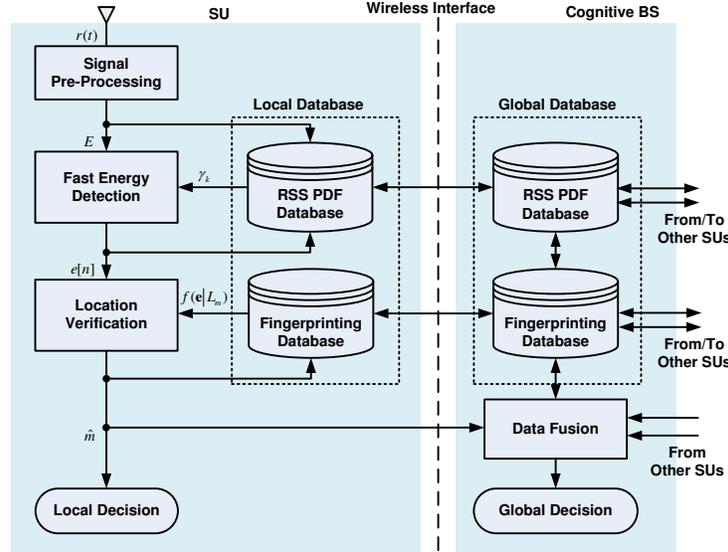


Fig. 4. Proposed database-assisted detection approach.

a high probability.

Generally, the received energy  $E$  has the form of a Chi-Square distribution. Since the number of samples is large in most cases, we can use the Central Limit Theorem (CLT) to approximate the Chi-Square distribution by a Gaussian distribution. Let  $H_0, H_1$  and  $H'_1$  denote the hypothesis of receiving no signal, a real PU signal and a PUE attack signal, respectively. Let  $P_d(\gamma_1, \gamma_2)$  and  $P_f(\gamma_1, \gamma_2)$  denote the PUE attack detection and false alarm probabilities, respectively. We have  $P_d(\gamma_1, \gamma_2) = \Pr\{\gamma_0 < E < \gamma_1 | H'_1\} + \Pr\{E > \gamma_2 | H'_1\}$ , and  $P_f(\gamma_1, \gamma_2) = \Pr\{\gamma_0 < E < \gamma_1 | H_1\} + \Pr\{E > \gamma_2 | H_1\}$ .

3) *Data Fusion driven Location Verification*: The proposed location verification does not need any dedicated positioning sensors [8]. In particular, suppose that the global database has recorded the location fingerprints of  $M$  PUE attackers as well as that of the real PU. The location verification will specifically identify the source of the received signal from the real PU and the PUE attackers. The location verification consists of three main steps. In step one, the SUs observe the input energy vector  $\mathbf{e}$  and estimate the location of the source by finding the best matching entry in their local databases. In step two, the SUs send the estimated location to the cognitive BS for data fusion. The cognitive BS makes a final decision and identifies the signal source. In step three, the cognitive BS updates the global database according to the gathered fingerprinting information from the multiple SUs. An update information is also sent to the SUs' local databases.

The location estimation using Bayesian hypothesis testing is described as follows. Let  $L_m$  ( $m = 0, 1, 2, \dots, M$ ) denote the location of the signal source, where  $L_0$  corresponds to the real PU and  $L_{\{1,2,\dots,M\}}$  correspond to the attackers, respectively. The input energy vector  $\mathbf{e}$  follows a parameterized probability density function with the parameter stored in the database. Specifically, the probability density function of  $\mathbf{e}$  under the hypothesis that the source is located in  $L_m$  is denoted  $f(\mathbf{e}|L_m)$ . The estimation of the location of the source of the signal is

given by

$$\hat{m} = \arg \max_{m=0,1,2,\dots,M} \pi_m f(\mathbf{e}|L_m) \quad (1)$$

where  $\pi_m$  is the a priori probability of the hypothesis that the source is located in  $L_m$ .

The estimated location  $\hat{m}$  is sent as the local decision to the cognitive BS for data fusion. The data fusion rules that lead to various global decisions are explained below.

- *True PU*: If all local decisions are identical and  $L_0$ , i.e.  $\hat{m} = 0$ , the cognitive BS will decide that the signal source is the true PU.
- *PUE attack in a known location*: If all local decisions are identical and  $\hat{m} \in L_{\{1,2,\dots,M\}}$ , the cognitive BS will decide that the source is the PUE attacker in location  $L_m$ .
- *PUE attack in a new location*: If the local decisions are different, the cognitive BS will decide that the source is a PUE attacker in a new location. A new fingerprint entry is added to the global database.

The final decision will be sent by the cognitive BS to the SUs. Both the local and global databases will be updated when a PUE attack is detected, either by the fast energy detector or by the location verifier. In particular, in the fast energy detector, the energy thresholds will be re-computed. In the location verifier, the probability density functions of the energy vector will be updated. In addition, if a new location of a PUE attacker is detected, a new profile will be created to track this new attacker. The communication overheads to update the two-level database is proportional to the frequency of PUE attacks. The computational complexity in detecting PUE attacks is determined by the number of samples in each spectrum sensing and the number of possible locations of the PUE attackers. The overall computational complexity is  $O(MN_s)$ , which is sufficiently low for practical deployment.

4) *Illustrative Result*: We consider a scenario where there are three PUE attackers located in positions  $L_1, L_2$  and  $L_3$ , respectively. The SUs are distributed in a circular field with

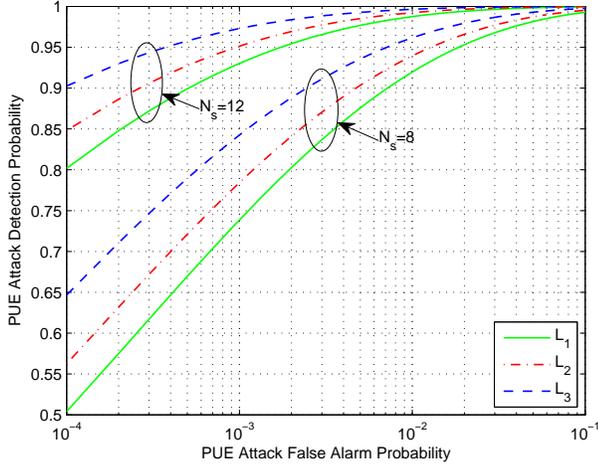


Fig. 5. PUE Attack detection probability in terms of false alarm probability.

radius 1 km. The primary BS is located in the center, while  $L_1$ ,  $L_2$  and  $L_3$  are respectively 100 m, 200 m, and 300 m away from the center. Fig. 5 demonstrates the effectiveness of the proposed detection approach. The PUE attack detection probability is shown in terms of the false alarm probability. In this example, we have shown two cases when the sampling parameter varies. The comparison indicates that more samples lead to higher detection probability. We can observe that, the farther the PUE attacker is located from the primary BS, the easier it is to detect it. For example, when  $N_s = 12$  and  $P_f = 0.1\%$ , the PUE attack detection probabilities are 0.93, 0.95 and 0.97 when the PUE attacks are performed from locations  $L_1$ ,  $L_2$  and  $L_3$ , respectively. The results indicate that the proposed approach works effectively and is able to successfully detect the attacks.

#### IV. DEFENSE APPROACHES AGAINST PUE ATTACKS

The defense against PUE attacks is an important but seldom explored topic in CR networks. There are practical requirements for efficient PUE attack defense approaches. We illustrate this by two examples below. First, although a variety of PUE attack detection approaches have been proposed, none of the existing approaches is able to promise accurate detection of all attacks. There still is a chance that some attacks are not detected. This necessitates system level mechanisms to maintain the overall performance of a CR network under undetected PUE attacks. Second, when there are malicious attackers in the network, their purpose is to interrupt the communications of the cognitive users. Even if they have been discovered, malicious attackers may still transmit in order to interfere with the transmissions of the SUs. In this case, the signal processing units in the RF front-ends of the SU receivers should be applied to get rid of the interference signals, in order to try to recover the secondary signal.

##### A. Defense Approaches at Various Protocol Layers

To defend against PUE attacks, effective counter measures could be taken at different layers of the communications protocol stack.

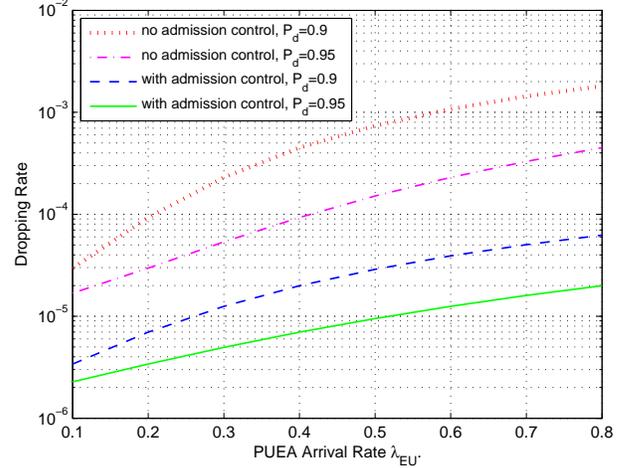


Fig. 6. Performance comparison in dropping rate of CR networks with and without admission control.

- *Physical-layer approach*: Physical-layer techniques such as source separation, signal design, spread spectrum and directional antennas could be employed to deal with the intended interference from malicious PUE attackers. The key in the design of an efficient physical-layer countermeasure is to exploit the a priori knowledge about the characteristics of the primary signal and its dissimilarity with the interference signal.
- *MAC-layer approach*: Undetected PUE attacks will steal bandwidth from the CR network. To let the SUs maintain moderate QoS performance, Radio Resource Management (RRM) strategies such as admission control, spectrum handoff and spectrum scheduling should be studied.
- *Network-layer approach*: In cognitive ad hoc networks, once the location of the PUE attackers are estimated, a position-based cognitive routing strategy could be employed to deal with the PUE attacks. Those SUs that are located within the attacking range of the PUE attackers should be considered to be temporary unavailable. End-to-end routing paths should be established without crossing the unavailable SU nodes.
- *Cross-layer approach*: A cross-layer design framework may be set up to defend against PUE attacks. In the framework, the behavior of the detected PUE attacks is observed at the physical layer and reported to the upper layers, such as the RRM mechanism at the MAC layer or the routing mechanism at the network layer. We emphasize that, even the undetected PUE attacks could be estimated in the physical layer by considering the theoretically derived detection probability. The control parameters of the upper layer are jointly optimized considering the existence of PUE attacks.

##### B. Admission Control to Defend Against PUE Attacks

In CR network, due to the nature of dynamic spectrum access, ongoing SU services may be forced to be drop in the presence of PUs. When a CR network suffers from

PUE attacks, the phenomenon of dropping will be severely magnified, leading to the discontinuity of SU services. A Guard Channel (GC) is a simple but effective approach to protect the ongoing services in a wireless networks. In this paper, we propose a GC-based admission control strategy to defend against PUE attacks. Upon the arrival of PUs or PUE attackers (if not detected), the ongoing services have to perform spectrum handoff. The handoff services need to acquire new available channels to resume the transmissions. Similar to conventional GCs, the proposed approach reserves a certain portion of the available channels for the handoff services. Once an SU needs a new channel for transmissions, it has to send a request message to the cognitive BS, applying for an available channel. The cognitive BS observes the remaining available channels. If the number of available channels is larger than the reservation number, the SU is allocated a new available channel. Otherwise, the SU's request is denied. The proposed GC strategy takes into account of the existence of PUE attacks, and has considered channel reservation for the PUE attacks. Hence, the dropping rate caused by PUE attacks could be significantly alleviated.

Fig. 6 compares the feature-based PUEA detection [9] without admission control and the feature-based PUEA detection with admission control. The results show that the introduction of admission control is able to significantly reduce the dropping rate. It is clear that the admission control based mechanism can significantly reduce the dropping rate. For instance, when  $P_d = 0.9$  and  $\lambda_{EU} = 0.8$ , the dropping rate is about  $1.8 \times 10^{-3}$  without admission control while it is only about  $6.2 \times 10^{-5}$  with admission control. Consequently, the proposed admission control based scheme can be applied as an efficient defense approach.

## V. CONCLUSION

This paper focuses on the PUE attack security problem in CR networks. A comprehensive introduction to PUE attacks is presented and several technical challenges are discussed, including classification of attackers, conditions for successful PUE attacks, and impacts of PUE attacks on CR networks. After that, a database-assisted detection approach is proposed to efficiently discover PUE attacks. Multi-threshold fast energy detection and fingerprint-based location verification are integrated and driven by a two-level database. In addition, an admission control based defense approach is proposed to alleviate the impact of PUE attacks on the performance of CR networks. By reserving a portion of channels for the handoff services, the dropping rate induced by successful PUE attacks could be evidently reduced. Illustrative results demonstrate that the reported detection and defense approaches are effective in discovering and defending PUE attacks in CR networks.

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