Attack Prevention for Collaborative Spectrum Sensing in Cognitive Radio Networks

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Abstract

Collaborative spectrum sensing can significantly improve the detection performance of secondary unlicensed users (SUs). However, the performance of collaborative sensing is vulnerable to sensing data falsification attacks, where malicious SUs (attackers) submit manipulated sensing reports to mislead the fusion center’s decision on spectrum occupancy. Moreover, attackers may not follow the fusion center’s decision regarding their spectrum access. This paper considers a challenging attack scenario where multiple rational attackers overhear all honest SUs’ sensing reports and cooperatively maximize attackers’ aggregate spectrum utilization. We show that, without attack-prevention mechanisms, honest SUs are unable to transmit over the licensed spectrum, and they may further be penalized by the primary user for collisions due to attackers’ aggressive transmissions. To prevent such attacks, we propose two novel attack-prevention mechanisms with direct and indirect punishments. The key idea is to identify collisions to the primary user that should not happen if all SUs follow the fusion center’s decision. Unlike prior work, the proposed simple mechanisms do not require the fusion center to identify and exclude attackers. The direct punishment can effectively prevent all attackers from behaving maliciously. The indirect punishment is easier to implement and can prevent attacks when the attackers care enough about their long-term reward.

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I. INTRODUCTION

Cognitive radios enable secondary unlicensed users (SUs) to opportunistically access licensed spectrum bands when they are not being used by primary licensed users (PUs), and thus can effectively improve spectrum utilization [10]. As a key technology for realizing opportunistic spectrum access while protecting PU communications, spectrum sensing aims to detect the presence or absence of a primary signal with high accuracy. To provide sufficient protection, spectrum sensing must be able to detect even a very weak primary signal, e.g., -20 dB for a DTV signal in the IEEE 802.22 WRANs [37]. To meet such stringent requirement, researchers have proposed the use of collaborative spectrum sensing to improve detection performance by exploiting sensor location diversity [11], [16], [30], [33]. In collaborative spectrum sensing, multiple sensors sense the spectrum individually and then report their sensing results to a central node (i.e., fusion center) for a final decision on spectrum occupancy.

Collaborative sensing, however, is vulnerable to critical attacks, such as sensing data falsification attacks, while its detection is difficult. In CRNs, sensors can be deployed in unattended and hostile environments, and thus can be compromised by attackers. Thus, compromised or malicious sensors can intentionally send distorted sensing results to the fusion center in order to disrupt the incumbent detection process [8], [23], [31]. Such attacks can be easily launched due to the openness of the low-layer protocols stacks of cognitive radio devices [44]. However, it is challenging for the fusion center to accurately validate the integrity of sensing reports because of the two unique features in spectrum sensing—unpredictability in wireless channel signal propagations and lack of coordination between PUs and SUs. The sensing data falsification attack will ultimately result in a waste of spectrum opportunities (in the form of false alarms), and/or excessive interference to the PU communications (in the form of missed detections). Therefore, this poses a significant threat to the implementation of cognitive radio technology, and thus calls for efficient attack detection and prevention mechanisms.

In this paper, we consider an attack scenario in which multiple attackers (i.e., compromised SUs/sensors) cooperate to maximize their aggregate spectrum utilization in cognitive radio networks (CRNs). Despite the serious threat posed by collaborated attacks, attacker collaboration have not been fully considered in CRNs. We focus on the particularly challenging attack scenario

1We use the terms “SU” and “sensor” interchangeably throughout the paper.
in which attackers can overhear all honest SUs’ sensing reports, whereas the honest SUs are unaware of the existence of attackers. This information asymmetry gives the attackers maximum capability to launch attacks and achieve their goals. We design attack-prevention mechanisms that safeguard collaborative sensing in such a challenging attack scenario, which constitutes the main contribution of this paper.

We consider two different attack scenarios: the “attack-and-run” scenario in which attackers only care about an immediate reward, and the “stay-with-attacks” scenario in which attackers care about the long-term reward. We first analyze the impact of attacks on honest SUs in the absence of attack-prevention mechanisms. Then, we propose two attack-prevention mechanisms: a direct punishment scheme that can effectively prevent attacks in both scenarios mentioned above, and an indirect punishment scheme that is easier to implement and effectively prevents attacks in the “stay-with-attacks” scenario. The key idea of both mechanisms is to discourage attackers from launching attacks by designing efficient attack detection and punishment strategies.

The key results and organization of this paper are summarized as follows.

- **A spectrum-sharing model with collision penalty:** In Sections II and III, we introduce the concept of collision penalty, which requires the SUs to compensate a PU for collision in utilizing the spectrum. The collision penalty is designed to protect the PU’s exclusive spectrum usage and encourage the PU’s opening of its licensed spectrum to SUs.

- **Understanding cooperative attackers’ optimal behaviors:** In Section IV, we theoretically show that in the absence of attack-prevention mechanisms, attackers will utilize all spectrum opportunities exclusively, whereas honest SUs cannot transmit and may even suffer from the collision penalty caused by attackers (see Table I).

- **Effective direct punishment:** In Section V, we design a direct punishment mechanism that can detect attacks and punish the attackers. This requires an efficient way for the fusion center to directly punish SUs. The proposed mechanism can prevent all attacks in both “attack-and-run” and “stay-with-attacks” scenarios (see Table I). We further show that a single attacker makes the network most vulnerable under this mechanism.

- **Effective indirect punishment:** In Section VI, we propose an indirect attack-prevention mechanism that is easy to implement when direct punishment is infeasible. The key idea is to terminate collaborative sensing when an attack is detected. The proposed mechanism can prevent all attacks if the attackers care enough about their long-term reward (see Table I).
TABLE I

**KEY RESULTS FOR DIFFERENT ATTACK SCENARIOS**

| Attack Scenarios | Attack-and-run | Stay-with-attacks |
|------------------|---------------|------------------|
| No Punishment (Sec. IV) | Attacks happen and honest SUs always lose transmission opportunities | |
| Direct Punishment (Sec. V) | Completely prevent attacks | |
| Indirect Punishment (Sec. VI) | Cannot prevent attacks | If attackers focus on long-term reward: completely prevent attacks; If attackers focus on short-term reward: partially prevent attacks. |

Unlike the direct punishment, the presence of a larger number of attackers may make the network more vulnerable.

A. Related Work

There has been a growing interest in attack-resilient collaborative spectrum sensing in CRNs (e.g., [8], [23]–[25], [31]). Liu et al. [5] exploited the problem of detecting unauthorized usage of a primary licensed spectrum. In this work, the path-loss effect is studied to detect anomalous spectrum usage, and a machine-learning technique is proposed to solve the general case. Chen et al. [23] focused on a passive approach with robust signal processing, and investigated robustness of various data-fusion techniques against sensing-targeted attacks. Kaligineedi et al. [25] presented outlier detection schemes to identify abnormal sensing reports. Min et al. [8] proposed a mechanisms for detecting and filtering out abnormal sensing reports by exploiting shadow-fading correlation in received primary signal strengths among nearby SUs. Fatemieh et al. [24] used outlier measurements inside each SU cell and collaboration among neighboring cells to identify cells with a significant number of malicious nodes. Li et al. in [31] detected possible abnormalities according to SU sensing report histories.

Our work is different from existing approaches in three aspects. First, we consider cooperation among attackers, so the attacks are much more challenging to prevent. Second, unlike the previous work which focused on sensing data falsification attacks, we also consider the case where the attackers violate the fusion center’s decision regarding spectrum access. Finally, our proposed attack-prevention mechanisms can easily prevent attacks without differentiating attackers from honest SUs.
Fig. 1. **An illustration of cooperative spectrum sensing in cognitive radio networks**: The figure shows a secondary network with $N = 6$ SUs including $M = 2$ malicious SUs (i.e., attackers). The SUs periodically perform spectrum sensing and report the local (binary) decisions to the fusion center (the solid arrows). The fusion center makes a final decision and announces it to the SUs (the dotted arrows).

II. **Preliminary**

A. **CRN Model and Assumptions**

We consider an infrastructure-based secondary CRN, which consists of a single base station (or fusion center) and a set of SUs (or sensors). The fusion center coordinates SUs’ collaborative spectrum sensing and their access to a licensed PU channel. We assume that the fusion center is maintained by a trusted network administrator and has high computation power. For collaborative spectrum sensing, all SUs (i) measure the primary signal strength on the same target channel, (ii) make local binary decisions on the presence or absence of the primary signal, and (iii) report the binary decisions to the fusion center [11], [21]. Based on the reported sensing results, the fusion center makes a global decision and broadcasts this result to the SUs.

There is a set of $\mathcal{N} = \{1, \ldots, N\}$ SUs in the network, $M$ of which are attackers as shown in Fig. 1. We assume that there is at least one honest SU in the network, i.e., $N - M \geq 1$; otherwise, it would be infeasible to defeat attacks. The honest SUs fairly share the licensed channel among themselves when the channel is available to them (i.e., it is not being used by the PU). The attackers (i.e., malicious or compromised SUs), on the other hand, behave to maximize their own aggregate reward (e.g., achievable throughput) by manipulating their sensing reports so that the fusion center makes a wrong decision. In particular, we focus on the case that attackers can overhear all honest SUs’ sensing reports to the fusion center before they collaboratively
manipulating their sensing results. We assume that attackers can communicate with each other (and thus know the number of attackers), while the honest SUs only communicate with the fusion center. The honest SUs do not have to be strategic, and they do not need to make decisions by considering other honest SUs and attackers’ decisions. In other words, the honest users do not play a game with the attackers.

To make the analysis tractable and obtain useful engineering insights, we make the following assumptions throughout the paper.

**A1.** All SUs have the same detection performance in terms of primary false alarm ($P_f$) and missed detection ($P_m$) probabilities.

**A2.** The PU’s spectrum occupancy is the same for all SUs and is independent across different time slots.

**A3.** All SUs have the same transmission rate in utilizing the channel.

In Appendix B, we relax both assumptions **A1** and **A3** by studying SUs’ heterogeneous detection performances and heterogeneous transmission rates. We will focus on the most challenging case of single attacker (as shown in Theorem 2 and Observation 1 in Section V), and show that the direct punishment mechanism proposed in Section V can still prevent all attacks. Similarly, the effectiveness of the indirect punishment mechanism proposed in Section VI can also apply to the two heterogeneous scenarios.

Regarding the PU’s temporal channel usage statistics, we denote $P_I$ as the probability that the channel is actually idle. Thus, the channel is busy with the probability $1 - P_I$. We assume that SUs (including attackers and fusion center) know the probability $P_I$ before collaborative spectrum sensing as in [7], [9], [31]. This is reasonable if SUs and fusion center can collect PU’s activity information from PU side and calculate $P_I$ using various methods as in [3]. Such...

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2A false alarm occurs when an SU detects an idle channel as busy, and a missed detection occurs when an SU detects a busy channel as idle. The detection performance depends on the SU’s physical location (relative to the primary transmitter) and fading environment.

3This is true when SUs stay relatively close compared to the PU’s coverage area.

4This assumption is frequently used in the literature (e.g., [7], [9], [31]), and is reasonable when we try to approximate the case where PU’s traffic changes fast (e.g., wireless microphones) and the time slot is relatively long. We may need to study the correlation between spectrum occupancies when PU’s traffic changes slowly over time (e.g., TV transmitters). Analyzing the correlated case requires a much more complicated Markov decision process (MDP) model than the one that we used in Section VI and we consider this as a future direction.
information collection is possible for SUs by examining PU’s published historical activity report or purchasing the history report from PU directly. Actually, the precision of $P_I$ does not affect SUs’ decisions and our analytical results. This is because attackers and the fusion center make decisions based on their belief of $P_I$.

B. Spectrum Sensing and Opportunistic Access Model

We assume a time-slotted model for opportunistic spectrum access, as in Fig. 2. Such time-slotted channel access model has been widely assumed in the literature [19], [34], [43], including the IEEE 802.22 standard draft [37]. Each time slot consists of two phases:

- Phase I (Collaborative Spectrum Sensing): As shown in Fig. 1, each SU performs sensing individually and makes a local binary decision (i.e., 0/1) on channel occupancy: 1 if it detects the PU’s signal (i.e., busy), and 0 otherwise (i.e., idle). All honest SUs truthfully report their sensing decisions to the fusion center. The attackers, on the other hand, overhear the sensing reports from the honest SUs before sending their own reports (which may be different from their actual local sensing decisions) to the fusion center. Based on the reports from all SUs (including the attackers), the fusion center makes a global decision and broadcasts it to all SUs in the network. We assume that the sensing reports and announcements are communicated via a dedicated and reliable control channel with no communication errors. Under this one-hop network configuration, the attackers can overhear the control channel and easily decode honest SUs’ reports like the fusion center. Also, even if we extend this

\[5^\text{Note that end-to-end encryptions of reports sent from SUs to the fusion center could be too complicated and expensive to implement to prevent attackers’ overhearing, as the control channel often can only support very low data rate transmissions.}\]
one-hop communication network to a multi-hop network, it is still possible for attackers to overhear all honest SUs’ reports as long as one attacker is located near the fusion center.

- **Phase II (Spectrum Sharing):** If the fusion center announces the channel to be idle, then honest SUs will transmit in Phase II. If it announces the channel to be busy, then honest SUs will wait. The attackers may transmit or wait in both cases. We assume that SUs who transmit in Phase II equally share the transmission time. More advanced link scheduling and power control may improve the overall network performance in Phase II, but is not the focus of this paper. Let us normalize the total transmission rate of the channel to $1$. More specifically, $X$ SUs transmitting together leads to $1/X$ rate for each involved SU by using TDMA mode.

To summarize, the attackers can launch attacks in two different ways: (i) in Phase I by reporting falsified sensing results, and (ii) in Phase II by disobeying the fusion center’s announcement.

### C. Collision Penalty

In order to increase social welfare, the government regulatory bodies (e.g., FCC in the U.S. and Ofcom in the U.K.) are pushing new spectrum-sharing schemes to allow the coexistence of PUs and SUs. There are two main obstacles in persuading PUs to share their licensed spectrum bands: (i) PUs’ fear of interference or service disruption caused by SUs, and (ii) lack of economic incentives to PUs for spectrum sharing. To achieve these goals while efficiently preventing attacks, we adopt the notion of “collision penalty”, similar in [40], as an incentive mechanism to allow for an efficient PU-SU coexistence. When a collision happens, we assume that the PU will charge a collision penalty $C_p$ to all SUs in the network. This collision penalty will compensate PUs for potential performance loss due to collisions.

The reasons why PU charges all SUs are as follows.

- **Complexity consideration:** If the PU does not know each SU’s transmission characteristics (e.g., modulation and coding schemes), it is impossible for him to check which subset of SUs cause collision. Also, the attackers can secure their transmissions (e.g., via MAC-layer

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$^6$If the total transmission rate of the channel is $r (\neq 1)$, we can change $C_p$ and $C_b$ (defined later in the paper) to $C_p/r$ and $C_b/r$ and all results will go through.

$^7$The penalty $C_p$ can be in the form of monetary payments from SUs, or reduced transmission opportunities of SUs, or cooperative transmission by SUs to improve the PU’s performance [22], [40].
encryptions) to avoid being detected and identified. Moreover, it is highly complex and
time-consuming for the PU to identify which SUs cause usage collision. Such identification
incurs a detection delay and is thus not desirable [8, 24, 25].

• Responsibility consideration: In the cooperative spectrum sensing, each SU contributes its
sensing result to the final decision of the fusion center, and each regular SU follows the
final decision. If a missed detection occurs, the PU should believe all SUs to be responsible
for their imperfect sensing. Even some missed detection events are caused by attackers, it
is impossible for the PU (without sensing reports) to identify and punish attackers only.

Based on the above discussion, we define the PU’s expected utility in one time slot as the
sum of the PU’s successful transmission rate and collision penalty collected from \( N \) SUs, i.e.,

\[
U_{PU}(C_p) = (1 - \gamma(C_p))V(r_{PU}) + \gamma(C_p)NC_p, \tag{1}
\]

where \( \gamma(C_p) \) is the collision probability of the PU’s transmission due to SUs’ aggressive access
and is decreasing in \( C_p \), \( r_{PU} \) is the PU’s transmission rate, and \( V(r_{PU}) \) is PU’s utility of achieving
rate \( r_{PU} \). A larger \( C_p \) makes SUs more conservative in spectrum access and leads to a lower
\( \gamma(C_p) \). Hence, a larger \( C_p \) achieves a high successful transmission rate (in the first term in
Eq. (1)), but may also lead to a low compensation from SUs (the second term in Eq. (1)).

### III. Decision Fusion Rule

Of the various decision fusion rules for collaborative sensing, we adopt the commonly used
OR-rule. Ghasemi and Sousa [38] showed that the OR-rule performs better than other rules
in many cases of practical interest. Here we will discuss the OR-rule as a special case of the
general \( n \)-out-of-\( N \) rule, and derive the conditions of \( C_p \) under which the OR-rule is theoretically
optimal. We elaborate the decision fusion rule by focusing on the case in which all SUs are
honest.

At the end of Phase I in each time slot (see Fig. 2), the fusion center collects a binary sensing
report \( D_i \in \{0 \text{ (idle)}, 1 \text{ (busy)}\} \) from each SU \( i \in \mathcal{N} \), and makes a decision using the following
\( n \)-out-of-\( N \) rule [11]:

\[
\begin{align*}
\mathcal{H}_0 & (\text{primary signal does not exist}) : \text{ if } \sum_{i \in \mathcal{N}} D_i < n. \\
\mathcal{H}_1 & (\text{primary signal exists}) : \text{ if } \sum_{i \in \mathcal{N}} D_i \geq n
\end{align*}
\tag{2}
\]
According to Eq. (2), the fusion center infers the channel to be busy $H_1$ when at least $n$-out-of-$N$ SUs report 1 (busy); otherwise, it infers the channel to be idle $H_0$. The optimal selection of the threshold $n$ depends on the system parameters and the reward functions of the SUs [21]. When $n = 1$, we have the OR-rule.

We show that when both of the following conditions hold, the OR-rule provides the highest reward for each SU within the family of $n$-out-of-$N$ rules.

1) When all SUs report 0 (i.e., $\sum_{i \in N} D_i = 0$), each SU obtains a positive expected reward by sharing the spectrum opportunity after taking into account the false alarm and missed detection probabilities:

$$Pr\left(\text{idle} | \sum_{i \in N} D_i = 0\right) \frac{1}{N} - Pr\left(\text{busy} | \sum_{i \in N} D_i = 0\right) C_p > 0. \quad (3)$$

The expected reward is the difference between the expected transmission rate and the collision penalty. Here, idle and busy denote the actual state of the channel instead of the fusion center’s announcement (i.e., $H_0$ or $H_1$).

2) When at least one SU reports 1 (i.e., $\sum_{i \in N} D_i \geq 1$), every SU obtains a negative expected reward by sharing the spectrum opportunity:

$$Pr\left(\text{idle} | \sum_{i \in N} D_i \geq 1\right) \frac{1}{N} - Pr\left(\text{busy} | \sum_{i \in N} D_i \geq 1\right) C_p < 0. \quad (4)$$

We can write these two conditions more compactly by defining the following two notations:

$$P_{I_{N,k}} = Pr\left(\text{idle} | \sum_{i \in N} D_i = k\right) = \frac{P_t(1 - P_f)^{N-k} P_f^k}{P_t(1 - P_f)^{N-k} P_f^k + (1 - P_t)(1 - P_m)^{N-k}(1 - P_m)^k}, \quad (5)$$

$$P_{B_{N,k}} = Pr\left(\text{busy} | \sum_{i \in N} D_i = k\right) = 1 - P_{I_{N,k}}. \quad (6)$$

Notice that $P_{I_{N,k}}$ in Eq. (5) is decreasing in $k$, and $P_{B_{N,k}}$ in Eq. (6) is increasing in $k$. Thus, Eq. (4) is decreasing in $\sum_{i \in N} D_i = k$. This implies that with more SUs reporting 1, SUs have less incentive to transmit. We can summarize the range of $C_p$ satisfying both Eqs. (3) and (4) as follows.

**Theorem 1:** At the fusion center, the OR-rule outperforms the other $n$-out-of-$N$ rules ($n > 1$) when the collision penalty $C_p$ satisfies the following condition.

**Condition I:**

$$\frac{P_t}{1 - P_t} \left(\frac{1 - P_f}{P_m}\right)^N \frac{1}{N (1 - P_m)(1 - P_f)} < C_p < \frac{P_t}{1 - P_t} \left(\frac{1 - P_f}{P_m}\right)^N \frac{1}{N}. \quad (7)$$
Fig. 3. $C_p$ range for the OR-rule’s optimal application with $(P_I, P_f, P_m) = (0.6, 0.08, 0.08)$.

The lower-bound of $C_p$ in Condition $I$ discourages the SUs from transmitting when at least one SU reports 1 (busy). The upper-bound of $C_p$ in Condition $I$ encourages SUs to transmit when all $N$ SUs report 0 (idle). In the rest of the paper, we assume that $C_p$ always satisfies Condition $I$.

In Region II of Figure 3, the OR-rule outperforms the other $n$-out-of-$N$ rules with various number of SUs and collision penalty $C_p$. As the number of SUs increases, the bounds on $C_p$ increase. For a fixed $C_p$, more SUs lead to the increase of false alarm probability and the decrease of missed detection probability for the whole system. Then the SUs tend to strategically transmit more aggressively even when some SU(s) reports 1 (busy). To prevent this and ensure the optimality of the OR-rule, a higher value of $C_p$ is required. The other decision fusion rules in Region III of Fig. 3 is not the focus of this paper. However, our analysis of the OR-rule can still apply to Region III, since in later analysis we consider all possible $C_p$ values and do not restrict our attention to Condition $I$.

IV. ATTACKERS’ BEHAVIORS WITHOUT PUNISHMENT

In this section, we analyze the behavior of cooperative attackers when the system lacks attack-prevention mechanisms. The results in this section will serve as a benchmark for the proposed attack-prevention mechanisms in Sections V and VI.

We first define some useful notations.

8According to 802.22 WRAN standard, $P_f$ and $P_m$ must be less than 10% [37].
• **State set** $S$: A state $s \in S$ describes the local sensing decisions of the honest SUs and attackers: $(\sum_{i \in \mathcal{N} \setminus \mathcal{M}} D_i, \sum_{i \in \mathcal{M}} D_i)$. The size of set $S$ is $(N - M + 1)(M + 1)^9$. The attackers know the exact state in a particular time slot by overhearing the honest SUs’ reports to the fusion center.

• **Attackers’ action set** $\mathcal{A}$: The action $a_m$ of an attacker $m \in \mathcal{M}$ is a tuple, (report to the fusion center in Phase I, spectrum access decision in Phase II), which has 4 possibilities: (idle, wait), (busy, wait), (idle, transmit), and (busy, transmit). Define $a = \{a_m, \forall m \in \mathcal{M}\}$ as the action vector of all attackers, and $\mathcal{A}$ includes all possible $a$.

• **Attackers’ expected aggregate reward** $R(a, s)$: This reward depends on the state $s$ and the attackers’ actions $a$ in one time slot. It denotes the difference between the attackers’ aggregate transmission rate and their expected payment to PU due to usage collision in one time slot.

For each state $s$, the attackers choose $a$ to maximize the expected aggregate reward in a single time slot, i.e.,

$$\max_{a \in \mathcal{A}} R(a, s). \quad (8)$$

We discuss the solution to Eq. (8) in the three following cases.

A. All SUs sense the channel idle

**Proposition 1**: Given the state $s = \left(\sum_{i \in \mathcal{N} \setminus \mathcal{M}} D_i = 0, \sum_{i \in \mathcal{M}} D_i = 0\right)$, the cooperative attackers’ optimal actions are: at least one attacker adopts the action (busy, transmit) and the other attackers (if any) adopt the action (idle, transmit). That is, at least one attacker will report the channel busy in Phase I and all attackers will transmit exclusively over the channel in Phase II. The fusion center will announce a wrong decision $\mathcal{H}_1$ in this case. The attackers’ expected aggregate reward is:

$$R(a, s) = P_{N,0}^I - MP_{N,0}^B C_p > 0, \quad (9)$$

where the definitions of $P_{N,0}^I$ and $P_{N,0}^B$ are given in Eqs. (5) and (6), respectively. An honest SU does not transmit, but may suffer from the collision penalty caused by attackers and receives a

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9The value of $D_i$ can be either 0 or 1, thus $\sum_{i \in \mathcal{N} \setminus \mathcal{M}} D_i$ ranges from 0 to $N - M$ and $\sum_{i \in \mathcal{M}} D_i$ ranges from 0 to $M$.

10Note that if all attackers have the same action sets, the fusion center may find it easier to identify them by checking their reports over time.
negative expected reward

\[ R_{honestSU}(s) = -P_{N,0}^B C_p < 0. \]  

**Proof.** Given the state \( s = \left( \sum_{i \in N \setminus M} D_i = 0, \sum_{i \in M} D_i = 0 \right) \) in a time slot, the attackers may report truthfully and falsely in the Phase I:

- If all attackers report 0 (i.e., \( \sum_{i \in M} \tilde{D}_i = \sum_{i \in M} D_i = 0 \)) in Phase I, then the announcement at the fusion center is \( H_0 \) and all honest SUs will transmit. Consider \( M_T \) (\( 0 \leq M_T \leq M \)) attackers choosing to transmit rather than wait in Phase II. The attackers’ expected aggregate reward in this time slot is:

\[ R_a(s)(M_T) = M_T \left( P_{N,0}^I \frac{1}{N - M + M_T} \right) - M P_{N,0}^I C_p, \]

which is increasing in \( M_T \). Thus all attackers will transmit, i.e., \( M_T = M \). Then the attackers’ expected aggregate reward is

\[ R_a(s) = M \left( P_{N,0}^I \frac{1}{N} - P_{N,0}^B C_p \right) > 0, \]  

(11)
due to Condition I in (7).

- If at least one attacker reports 1 (i.e., \( \sum_{i \in M} \tilde{D}_i \geq 1 \)) in Phase I, then the announcement at the fusion center is \( H_1 \) and all honest SUs will not transmit.

  - Consider \( M_T \) (\( 1 \leq M_T \leq M \)) attackers choosing to transmit. The attackers’ expected aggregate reward is given by (9), which does depend on \( \tilde{M} \) and is larger than (11).

  - If all attackers wait, the attackers’ expected aggregate reward equals 0, which is less than (9).

By comparing (11) and (9) with different actions, we conclude that at least one attacker will report 1 and steal the opportunity from honest SUs to utilize the channel exclusively. As a result, all honest SUs will not transmit but may suffer the collision penalty as in (10).

Proposition 1 shows that an attack always happens when all SUs sense the channel idle.

**B. All honest SUs sense the channel idle, but some attacker(s) senses the channel busy**

Here we define the attackers’ aggregate sensing result \( \sum_{i \in M} D_i \) as \( \bar{M} \).

**Proposition 2:** Given the state \( s = \left( \sum_{i \in N \setminus M} D_i = 0, \sum_{i \in M} D_i = \bar{M} \geq 1 \right) \), the cooperative attackers’ optimal actions are as follows.
• If $P^I_{N,M} < MP^B_{N,M}C_p$, then at least one attacker adopts the action (busy, wait) and the other attackers (if any) adopt the action (idle, wait). This leads to a correct announcement $\mathcal{H}_1$ (busy) at the fusion center. Since no one transmits, the attackers and the honest SUs all get zero reward,

$$R(a, s) = R_{honestSU}(s) = 0.$$  \hspace{1cm} (12)

• If $P^I_{N,M} \geq MP^B_{N,M}C_p$, then at least one attacker adopts the action (busy, transmit) and the other attackers (if any) adopt the action (idle, transmit). This leads to a correct announcement $\mathcal{H}_1$ (busy) at the fusion center. Only attackers will transmit exclusively in Phase II, their expected aggregate reward is:

$$R(a, s) = P^I_{N,M} - MP^B_{N,M}C_p > 0.$$  \hspace{1cm} (13)

An honest SU does not transmit in Phase II, but may suffer from the collision penalty caused by attackers’ transmissions and receives a negative expected reward

$$R_{honestSU}(s) = -P^B_{N,M}C_p < 0.$$  \hspace{1cm} (14)

Proof. Given the state $(\sum_{i \in N \setminus M} D_i = 0, \sum_{i \in M} D_i = \bar{M} \geq 1)$ in one time slot, the attackers may report truthfully or falsely in Phase I:

• If all attackers report 0 (i.e., $\sum_{i \in M} \tilde{D}_i = \sum_{i \in M} D_i = 0$) in Phase I, then the announcement at the fusion center is $\mathcal{H}_0$ and all honest SUs will transmit. Similar to the proof in Subsection [IV-A] it is optimal for all attackers to transmit. Their expected aggregate reward is:

$$R_a(s) = M \left( P^I_{N,M} \frac{1}{N} - P^B_{N,M}C_p \right) < 0,$$  \hspace{1cm} (15)

due to Condition.I in (7).

• If at least one attacker reports 1 (i.e., $\sum_{i \in M} \tilde{D}_i \geq 1$) in Phase I, then the announcement at the fusion center is $\mathcal{H}_1$ and all honest SUs will not transmit.

  – If at least one attacker transmits in Phase II, the attackers’ expected aggregate reward is given by (13). Notice that (13) is negative only if the collision penalty is high enough.

  – If all attackers wait in Phase II, the attackers’ expected aggregate reward equals 0.

By comparing (13) and 0 with different actions, we conclude that at least one attacker will report 1 to ensure that the correct announcement is made at the fusion center. But the attackers may transmit over the channel exclusively and the honest SUs may suffer from the collision penalty caused by the attackers with an expected reward in (14).
Proposition 2 indicates that an attack only happens when the benefit of exclusive transmission is large enough to compensate the potential collision penalty for the attackers.

C. Some honest SUs sense the channel busy

**Proposition 3:** Given the state \( s = \left( \sum_{i \in N \setminus M} D_i = K \geq 1, \sum_{i \in M} D_i = \bar{M} \geq 0 \right) \)\(^{11}\), the announcement at the fusion center is always correct with \( \mathcal{H}_1 \) (busy), and the attackers’ optimal actions are as follows.

- If \( P_{N,K+\bar{M}}^I < M P_{N,K+\bar{M}}^B C_p \), then each attacker can either take the action (busy, wait) or (idle, wait). Since no one transmits, the attackers and the honest SUs all get zero reward,
  \[
  R(a, s) = R_{\text{honestSU}}(s) = 0. \tag{16}
  \]

- If \( P_{N,K+\bar{M}}^I \geq M P_{N,K+\bar{M}}^B C_p \), then each attacker can either take the action (busy, transmit) or (idle, transmit). As only attackers will transmit in Phase II, their expected aggregate reward is:
  \[
  R(a, s) = P_{N,K+\bar{M}}^I - M P_{N,K+\bar{M}}^B C_p. \tag{17}
  \]

An honest SU does not transmit in Phase II, but may suffer from the collision penalty caused by attackers’ transmissions and receives a negative expected reward

\[
R_{\text{honestSU}}(s) = -P_{N,K+\bar{M}}^B C_p < 0. \tag{18}
\]

**Proof.** Given the state \( s = \left( \sum_{i \in N \setminus M} D_i = K \geq 1, \sum_{i \in M} D_i = \bar{M} \geq 0 \right) \), no matter what attackers report in Phase I, the announcement at the fusion center is always \( \mathcal{H}_1 \), and the honest SUs will not transmit in Phase II.

- If some attackers transmit in Phase II, the attackers’ expected aggregate reward is given by (17).
- If all attackers wait in Phase II, the attackers’ expected aggregate reward equals 0. Each honest SU’s immediate expected reward also equals 0.

By comparing (17) to 0, we conclude that the fusion center always makes the correct announcement \( \mathcal{H}_1 \) regardless of the attackers’ reports. However, the attackers may transmit over the channel exclusively in Phase II, and the honest SUs may suffer from the collision penalty caused by the attackers with expected reward in (18).

\(^{11}\)Note that this state includes the case that all honest SUs sense the channel busy and (some) attackers sense idle.
TABLE II
ATTACKERS’ OPTIMAL BEHAVIORS AND HONEST SUs’ BEHAVIORS

| Sensing Decisions | Attackers’ optimal behaviors                                                                 | Honest SUs’ behaviors |
|-------------------|----------------------------------------------------------------------------------------------|-----------------------|
| \( \sum_{i \in N} D_i = 0 \) | Attack by reporting falsely and transmitting exclusively                                             | Wait                  |
| \( \sum_{i \in N} D_i = K \geq 1 \) | If \( P_{N,K}^A < MP_{N,K}^B C_p \), do not attack. If \( P_{N,K}^A \geq MP_{N,K}^B C_p \), attack by reporting truthfully and transmitting exclusively | Wait                  |

We summarize the results in Propositions 1-3 as in Table II. Without any attack-prevention mechanism, the attackers will utilize the spectrum opportunities exclusively, whereas the honest SUs will never transmit regardless of their sensing decisions. What is worse, the honest SUs may suffer from the collision penalty caused by the attackers.

Note that our current analytical results focus on one time slot, where the attackers want to maximize their expected aggregate reward in the current time slot (i.e., the “attack-and-run” scenario). Since attackers’ behaviors are independent over time slots, the above analytical results also hold for the “stay-with-attacks” scenario.

Given many possible attack scenarios in Section IV, it is hard to identify attackers based on their report orders and results in Phase I. The reasons are as follows.

- First, different SUs may have different sensing times to guarantee certain precision of channel detection, and thus it is not possible to force everyone to report at the same time. This means that there is always a last reporter. If all SUs are honest, then the last reporter is not an attacker. Unless the fusion center is sure that there exists at least one attacker, it is hard to tell that the last reporting SU is an attacker.
- Second, even the fusion center is aware of attacker(s), it is still difficult to punish attackers effectively since the attackers (aware of such identification) can strategically change to report not the last.
  - When the attackers overhear some honest SU(s) reporting 1 (busy) at the beginning, they can report immediately after their sensing and do not need to wait for the last honest SU’s report. In this case, the fusion center’s decision is correct (\( H_1 \)) no matter attackers’ manipulate their reports or not. But the attackers can still attack (i.e., violating...
the fusion center’s decision and transmit) as shown in Case C in Section IV. In this case, the attackers still need to overhear all honest SUs’ reports.

- When the attackers overhear many honest SUs’ reporting 0 (idle), they may not wait for the last honest SU’s report and can still manipulate their reports. In this case, such identification still hurts honest SU(s) and the attackers still perform attacks although they lose a little bit of information.

It should also be noted that it is possible for the fusion center to monitor the control channel to check who are the attackers by exchanging their sensing results secretly in Phase I. It is also possible that the fusion center can monitor the PU’s licensed later to see who disobey its decision to transmit exclusively. But the above attack identifications require the fusion center to know at least all SUs’ coding and modulation schemes. Even the fusion center has such information, the attackers can still change their coding and modulation schemes (e.g., as some honest SUs), or secure their communication to exchange sensing results in Phase I and their transmission in Phase II, e.g., via MAC-layer encryptions, to avoid being identified by the fusion center.

The above discussions illustrate why we are interested in designing attack-prevention mechanisms without attack identification.

V. ATTACK-PREVENTION MECHANISM: A DIRECT PUNISHMENT

In this section, we consider the case in which the fusion center can directly charge a punishment to the SUs when attacks are identified. We focus on the “attack-and-run” scenario in a single time slot. The analysis also applies to the “stay-with-attacks” scenario as in Section IV. With the proper choice of punishment, the proposed mechanism ensures that no attack will happen and no one will be punished.

Let us denote the direct punishment as $C_b$, which is different from the collision penalty $C_p$ introduced in Section II-C. The fusion center will only charge the punishment to all SUs when the PU detects an attack. Let us consider the following two scenarios:

- When the announcement at the fusion center is $H_1$ (busy) in Phase I and a collision happens in Phase II, the fusion center knows that an attack happens (as honest SUs will not transmit in Phase II). In this case, all SUs are charged a direct punishment $C_b$ by the fusion center.
Fig. 4. Direct punishment threshold $C_b^{th}(M)$ for different $M$ and $N$ cases with $(P_I, P_f, P_m, C_p) = (0.6, 0.08, 0.08, 6e + 10)$.

(in addition to the collision penalty $C_p$ charged by the PU)\(^\text{12}\)

Note that when the announcement at the fusion center is $\mathcal{H}_0$ (idle) in Phase I, no direct punishment will be triggered even if there is a collision in Phase II. This is because attackers will not share the spectrum access opportunity with honest SUs as in Proposition \(\text{I}\) and such collision can only the result of the missed detections of spectrum sensing.

The effectiveness of the attack-prevention mechanism depends on the choice of the punishment $C_b$. Theorem \(\text{2}\) shows that a large enough $C_b$ can prevent all possible attacks.

**Theorem 2**: For $M$ attackers in the network, there exists a threshold $C_b^{th}(M)$, i.e.,

$$C_b^{th}(M) = \frac{P_I}{1 - P_I} \left(\frac{1 - P_f}{P_m}\right)^N \max \left(\frac{P_f P_m}{(1 - P_f)(1 - P_m)} \frac{1}{M} - C_p, \left(\frac{1}{M} - \frac{1}{N}\right)\right), \quad \forall M \geq 1,$$

such that any value $C_b > C_b^{th}(M)$ can prevent all attack scenarios described in Section \(\text{IV}\).

The proof of Theorem \(\text{2}\) is given in Appendix \(\text{A}\). Next, we examine how the numbers of honest SUs and attackers affect the threshold $C_b^{th}(M)$.

**Observation 1**: $C_b^{th}(M)$ is decreasing in the number of attackers $M$ and increasing in the number of honest SUs $N - M$. If the fusion center does not know the number of attackers, it

\(^{12}\)The way for the fusion center to realize the punishment $C_b$ is similar to the way to realize the collision penalty $C_p$. See footnote \(\text{7}\) for details.
should set the threshold to be $C_{b}^{th}(1) = \max_{M \geq 1} C_{b}^{th}(M)$ to prevent all attacks.

Figure 4 shows the value of threshold $C_{b}^{th}(M)$ as a function of $M$ for different values of $N$. When the number of attackers increases, the total penalty to the group of attackers also increases when an attack is confirmed (while the total transmission rate does not change), which discourages the attacks to happen.

Figure 4 also shows that $C_{b}^{th}(M)$ increases with the number of honest SUs $N - M$ for any fixed $M$. This is because the more honest SUs’ sensing reports are overheard by the attackers, the more accurately the attackers can estimate the actual channel state, and thus more likely the attackers will launch an attack. As a result, a higher $C_{b}$ is required to prevent attackers from manipulating their sensing reports. Thus, the single attacker scenario (i.e., $M = 1$) is the most challenging case for this attack-prevention mechanism.

**Observation 2:** The threshold $C_{b}^{th}(1)$ is increasing in the idle probability $P_I$ and non-increasing in the collision penalty $C_p$.

Figure 5 shows that the value of threshold $C_{b}^{th}(M)$ is increasing in the idle probability $P_I$. A larger $P_I$ means a higher channel availability, and thus encourages the attackers to launch an attack so that they can exclusively utilize the channel more frequently. A larger $C_p$ discourages

---

13Since $P_f$ and $P_m$ must be less than 10% in 802.22 WRAN standard draft, thus the probability to trigger direct punishment is very small under this choice of $P_f$ and $P_m$. As a result, high $C_{b}^{th}(M) = C_{b}^{th}(M)/r$ value is determined in Fig. 4 to eliminate the attack benefit.
the attackers from accessing the channel due to the possibility of paying a large collision penalty.

VI. ATTACK-PREVENTION MECHANISM: AN INDIRECT PUNISHMENT

The direct punishment scheme may be difficult to enforce for certain types of networks due to practical constraints, such as implementation overhead and complexity. For example, if the direct punishment is in the form of monetary payments from SUs to the fusion center, the fusion center needs to have reliable channels to collect and monitor such payments [22], [39]. In this section we propose an indirect punishment scheme that can effectively prevent attacks in the “stay-with-attacks” scenario as long as the attackers care enough about future rewards. The key idea is to terminate collaborative sensing once the fusion center detects an attack, which forces the attackers to rely on their own sensing results in the future. This prevents attackers from overhearing honest SU sensing reports, and results in an increase in missed detection probability for attackers. Therefore, such indirect punishment will reduce the attackers’ incentives to attack.

The indirect punishment works as follows:

- When the fusion center announces $H_1$ (busy) in Phase I and a collision happens in Phase II, the indirect punishment is triggered and there is no collaborative sensing in future time slots.\(^{14}\)

Note that when the fusion center announces $H_0$ (idle) in Phase I, no indirect punishment will be triggered even if there is a collision in Phase II.

Similar to the direct punishment mechanism in Section V, no indirect punishment will be triggered if all SUs behave honestly. The effectiveness of the indirect punishment depends on the attackers’ performance when they are isolated from the honest SUs.

In the rest of the section, we make the following assumption:

$$A4: C_p > \frac{P_f}{1 - P_f} \cdot \frac{1 - P_f}{P_m}. \quad (20)$$

$A4$ is derived from $P_{1,0}^f - P_{1,0}^B C_p < 0$, which implies that a single SU will not transmit based on its own sensing decision (since it can be quite unreliable after the collaborative sensing breaks down) even without interference from the other SUs. $A4$ is quite mild. When the number of

\(^{14}\)The fusion center can achieve this by broadcasting to all SUs that there is no need to report local sensing decisions in the future.
SUs is reasonable (i.e., \( N > 7 \)), Condition I in Eq. \((7)\) directly guarantees the satisfaction of \(A_4\) in Eq. \((20)\). Note that \(A_4\) only applies to this section.

To analyze the attackers’ dynamic decisions in the long-term “stay-with-attacks” scenario, we formulate the problem as a Markov decision process (MDP) \([18]\). More specifically, we consider an infinite horizon Markov decision process \((S', A', P, R)\), where the group of cooperative attackers is the only decision-maker (collectively) over time.

- **State set \(S'\):** A state \(s \in S'\) describes the attackers’ knowledge of honest SUs’ sensing decisions, their own sensing decisions, and whether the indirect punishment is triggered: \((\sum_{i \in N \setminus M} \bar{D}_i, \sum_{i \in M} D_i, \text{Punishment})\). When Punishment = off, \(\sum_{i \in N \setminus M} \bar{D}_i = \sum_{i \in M} D_i\). When Punishment = on, \(\sum_{i \in N \setminus M} \bar{D}_i\) is unknown as the attackers do not know the honest SUs’ sensing decisions. The size of set \(S'\) is \([((N-M+1)(M+1)+(M+1)]\).

  The attackers know the state during each time slot.

- **Attackers’ action set \(A'\):** The action \(a_m\) of an attacker \(m \in M\) is a tuple: (report to the fusion center, spectrum access decision). When the indirect punishment is not triggered, there are four possible actions: (idle, wait), (busy, wait), (idle, transmit), and (busy, transmit). When the indirect punishment is triggered, an attacker’s action can be \((N/A, \text{transmit})\) or \((N/A, \text{wait})\), where \(N/A\) means that the attackers do not report. We define \(a = \{a_m, \forall m \in M\}\) as the action vector of all attackers and \(A'\) contains all feasible values of \(a\).

- **Transition probability \(P(a, s, s')\):** The transition probability that actions \(a\) in a state \(s\) at time slot \(t\) will lead to state \(s'\) in time slot \(t+1\) is \(P(a, s, s') = Pr(s_{t+1} = s' | s_t = s, a_t = a)\).

  This depends on both state \(s\) and actions \(a\), and is independent of time \(t\).

- **Attackers’ expected aggregated reward \(R(a, s)\):** The attackers’ received reward after taking actions \(a\) in state \(s\) of a time slot.

  Compared to the reward in the current time slot, the attackers may value future rewards less. This can be captured by a discount factor \(\delta \in (0, 1)\). We further define a stationary policy \(u\) as a mapping between the set of states \(S'\) to the action set \(A'\). In other words, a policy defines what action to take in each possible state. The attackers’ objective is to choose a policy \(u\) from policy set \(U\) to maximize the long-term expected aggregate reward:

  \[
  \max_{u \in U} \sum_{t=0}^{\infty} \delta^t R(u(s), s), \tag{21}
  \]

  Let us denote the attackers’ optimal long-term expected aggregate rewards by \(LR^H\) and \(LR^{DH}\). 

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if they behave honestly and dishonestly, respectively.

Since attackers’ behaviors and rewards before and after the indirect punishment are quite different, we need to study them separately. Here we first consider the attackers’ behaviors before the punishment. Let us consider the case where at least one SU senses the channel busy, i.e., $\sum_{i \in N} D_i = K \geq 1$. The attackers’ optimal behaviors can be classified into two cases:

- **Non-aggressive Transmission**: The attackers will not attack for any $K \geq 1$, which is true if

\[
\text{Case. NT} : P_{N,1}^I - M P_{N,1}^B C_p < 0, \tag{22}
\]

where the attackers’ exclusive transmission opportunity does not compensate their collision penalty.

- **Aggressive Transmission**: The attackers may attack even if $K \geq 1$, which is true if

\[
\text{Case. AT} : P_{N,1}^I - M P_{N,1}^B C_p \geq 0. \tag{23}
\]

In the rest of this section, we focus on Case. NT with $M \geq 1$ attackers. The discussion for Case. AT with $M \geq 1$ is given in Appendix C.

We analyze the conditions under which attacks can be completely prevented via an indirect punishment. We first need to understand the attackers’ performance degradation once the indirect punishment is triggered. Since the attackers are cooperative, they can always exchange sensing information among themselves. Depending on whether the attackers will transmit after the indirect punishment, we have two cases:

- **Weak Cooperation**: The attackers will not transmit even when all attackers sense the channel idle,

\[
\text{Case. WC} : P_{M,0}^I - M P_{M,0}^B C_p \leq 0. \tag{24}
\]

This means that the attackers feel that their own sensing results are not reliable enough (with a high missed detection probability). Case. WC also implies that the attackers will definitely not transmit if one or more attackers sense the channel busy. Due to assumption A4, the reward in Eq. (24) is an increasing function of the number of attackers $M$. Then we can also write Eq. (24) as an upper bound of $M$, i.e., Case. WC corresponds to a small number of attackers $M$.

- **Strong Cooperation**: The attackers will transmit when all attackers sense the channel idle,

\[
\text{Case. SC} : P_{M,0}^I - M P_{M,0}^B C_p > 0. \tag{25}
\]
\[ \delta_{SC}^\text{th}(M) = \left(1 + \frac{(P_t(1-P_f))^N - (1-P_t)(P_m)^N C_p}{\frac{1}{M} - \frac{1}{N}} - (1-P_t)(P_m)^M C_p \right) \frac{1-P_t}{P_f} \left( \frac{P_m}{1-P_f} \right)^N \right)^{-1}. \]

(29)

This means that the attackers feel that their own sensing results (collectively) are accurate enough (with a low missed detection probability) even taking the collision penalty \( C_p \) into consideration. We can also write Eq. (25) as a lower bound of \( M \), i.e., \( \text{Case.SC} \) corresponds to a large number of attackers \( M \).

Obviously, it is more challenging to prevent attacks in \( \text{Case.SC} \) than \( \text{Case.WC} \). However, we can show that in \( \text{Case.SC} \) the attackers’ expected aggregate reward in one time slot with punishment triggered is always less than their reward when they always behave honestly. In other words, as long as the attackers care enough about future reward (i.e., the discount factor \( \delta \) is high enough), we can still prevent attacks even in \( \text{Case.SC} \) (and thus in \( \text{Case.WC} \) as well).

**Lemma 1:** The attackers’ optimal long-term expected aggregate rewards in \( \text{Case.WC} \) and \( \text{Case.SC} \) are

\[
LR_{HC}^H = LR_{SC}^H = Pr\left( \sum_{i \in N} D_i = 0 \right) \left( \frac{P^I_{N,0} 1}{N} - P^B_{N,0} C_p \right) \frac{M}{1 - \delta},
\]

(26)

\[
LR_{HC}^{DH} = \frac{Pr(\sum_{i \in N} D_i = 0)(P^I_{N,0} - MP^B_{N,0} C_p)}{1 - \delta(1 - Pr(\sum_{i \in N} D_i = 0)P^B_{N,0})},
\]

(27)

and \( LR_{SC}^{DH} \) in

\[
LR_{SC}^{DH} = LR_{WC}^{DH} + \frac{\delta}{1 - \delta} Pr\left( \sum_{i \in N} D_i = 0 \right) \frac{P^B_{N,0} Pr(\sum_{i \in M} D_i = 0)(P^I_{M,0} - MP^B_{M,0} C_p)}{1 - \delta(Pr(\sum_{i \in N} D_i > 0) + Pr(\sum_{i \in N} D_i = 0)P^B_{N,0})}.
\]

(28)

Here the superscripts “\( H \)” and “\( DH \)” indicates honest and dishonest behaviors of attackers, respectively.

The proof of Lemma 1 is given in Appendix D where we can show that \( LR_{WC}^{DH} < LR_{HC}^H \) and \( LR_{SC}^{DH} < LR_{WC}^H \) when \( \delta \) goes close to 1. This leads to the following result.

**Theorem 3:** The indirect punishment can prevent all attack in “stay-with-attacks” scenario if the discount factor \( \delta \) satisfies the following condition:

- **Weak cooperation (Case.WC):** for any \( 1 \leq M < N \), we need \( \delta > \delta_{WC}^\text{th}(M) \) where

\[
\delta_{WC}^\text{th}(M) = \frac{1}{1 + \frac{(P_t(1-P_f))^N - (1-P_t)(P_m)^N C_p}{\frac{1}{M} - \frac{1}{N}} - (1-P_t)(P_m)^M C_p \frac{1-P_t}{P_f} \left( \frac{P_m}{1-P_f} \right)^N}.
\]

(30)
• **Strong cooperation (Case.SC):** for any $1 \leq M < N$, we need $\delta > \delta_{SC}^{th}(M)$ where $\delta_{SC}^{th}$ is given in Eq. (29).

If the fusion center does not know the number of attackers, $M$, it can choose $\delta > \max_{0<M<N} \delta_{WC}^{th}(M)$ and $\delta > \max_{0<\leq M<N} \delta_{SC}^{th}(M)$ for the two cases, respectively.

Although it is not shown in Theorem 3, we want to mention that the indirect punishment can still partially prevent attacks even $\delta$ is less than the discount factor threshold. Intuitively, attackers do not want to trigger indirect punishment and lose the opportunity to overhear honest SUs’ sensing results. Thus they will behave more conservatively compared to the case with no indirect punishment. For example, if some SUs’ sensing results indicate a busy channel state, the attackers will not attack to trigger the long-term punishment.

We have the following interesting observations.

**Observation 3:** *(Impact of network size:)* Both $\delta_{WC}^{th}(M)$ in Case.WC and $\delta_{SC}^{th}(M)$ in Case.SC are increasing in the number of the honest SUs $N - M$. Threshold $\delta_{WC}^{th}(M)$ is decreasing in the number of the attackers $M$, while $\delta_{SC}^{th}(M)$ is increasing in the number of the attackers $M$.

Figure 6 plots $\delta_{SC}^{th}(M)$ as a function of $N$ and $M$ in Case.SC. The corresponding result in Case.WC can also be obtained based on Eq. (30).

With more honest SUs $N - M$, attackers have a less incentive to share the spectrum with honest SUs in the long-term and a higher incentive to attack and transmit exclusively. Thus a higher $\delta$ is needed to prevent attacks.
A larger number of attackers $M$ has two effects: (a) a higher total collision penalty (whenever a collision happens), and (b) attackers’ better estimation of channel condition (once the punishment is triggered). It turns out that effect (a) dominates in Case.WC and effect (b) dominates in Case.SC, which explains why the $\delta$ threshold decreases in $M$ in Case.WC and increases in $M$ in Case.SC. In Fig. 6 the most attack-vulnerable case happens when almost all SUs are attackers ($M \rightarrow N$), in which case $LR_{SC}^{DH} \rightarrow LR_{SC}^{SH}$ and $\delta_{SC}^{th}(M)$ in (29) is close to 1.

Observation 4: (Impact of collision penalty $C_p$) $\delta_{WC}^{th}(M)$ in Case.WC is increasing in the collision penalty $C_p$, while $\delta_{SC}^{th}(M)$ in Case.SC is decreasing in $C_p$.

In Case.WC, the collision penalty $C_p$ only affects the time slots before the punishment is triggered. A higher $C_p$ means a smaller long-term expected reward as a conservative honest SU (by comparing $LR_{WC}^{SH}$ in Eq. (26) to $LR_{WC}^{DH}$ in Eq. (27)), and thus more incentives to attack. In Case.SC, a larger value of $C_p$ hurts the reward of attackers more after punishment than before punishment. This is because the transmission probability before punishment is $Pr(\sum_{i \in N} D_i = 0)$ (i.e., all SUs sense idle), which is smaller than the transmission probability after punishment $Pr(\sum_{i \in M} D_i = 0)$ (i.e., all attackers sense idle). Thus a larger $C_p$ discourages the attacks in Case.SC.

VII. CONCLUSIONS AND FUTURE WORK

Collaborative spectrum sensing is vulnerable to sensing data falsification attacks. In this paper, we focused on a challenging attack scenario in which multiple cooperative attackers can overhear the honest SU sensing reports, but the honest SUs are unaware of the existence of attackers. We first analyzed all possible attack scenarios without any attack-prevention mechanisms. In this case, we showed that honest SUs will have no chance to transmit and may even suffer from the collision penalty charged by the PU. Then, we proposed two attack-prevention mechanisms with direct and indirect punishments. Both mechanisms do not require identification of the attackers. The direct punishment can effectively prevent all attacks in both “attack-and-run” and “stay-with-attacks,” and the indirect punishment can prevent all attacks in the long-run if the attackers care enough about their future rewards.

There are several possible ways to extend the results in this paper.

- First, we can consider the case where PU’s traffic changes slowly over time (e.g., TV
transmitters), where we need to consider the correlation between spectrum occupancies over different time slots. In this case, we should use a much more complicated MDP model than the one in Section VI.

- Second, we can study the case that the fusion center knows all SUs’ transmission characteristics (e.g., modulation and coding schemes) and can monitor attackers’ sensing information communication in Phase I and attackers’ transmissions in Phase II. In this case, the fusion center may be able to identify attackers. However, the attackers can change their modulation and coding schemes (e.g., as some honest SUs) or secure their transmissions (via MAC-layer encryptions) to avoid being identified.

- Third, we can study the denial-of-service attacks. Throughout this paper, we consider that attackers are rational and are only interested in maximizing their own rewards. For denial of service attacks, however, the attackers’ objective is to let honest SUs lose transmission opportunities or break down the effectiveness of collaborative sensing.

- Finally, we can consider imperfect control channel between SUs and the fusion center (e.g., some SUs receive false announcement from the fusion center). In that case, an indirect punishment can be triggered due to channel communication errors instead of attacks. We need to design the indirect punishment which will resume collaborative sensing after a period of time (instead of an infinitely long punishment).

**Appendix**

**A. Proof of Theorem 2**

By examining different possible states, we can derive the attackers’ optimal behaviors. Then in response to the attackers’ optimal behaviors, we find the proper value of direct punishment $C_b$ to prevent all attacks.

1) $\sum_{i \in N \backslash M} D_i = 0$, $\sum_{i \in M} D_i = 0$): When the sensing results are all 0, then the attackers may report truthfully or falsely in the Phase I:

- If all attackers report 0 in Phase I, then the announcement at the fusion center is $H_0$ (idle), and all honest SUs will transmit. It is easy to check that all attackers will transmit with positive expected aggregate reward in (11).
- If some attackers report 1 in Phase I, then the announcement at the fusion center is $H_1$ (busy) and all honest SUs will not transmit.
– If some attackers with number $1 \leq M_T \leq M$ choose to transmit, the attackers’ expected aggregate reward is:

$$R_a(s) = P_{N,0}^I - M P_{N,0}^B (C_p + C_b).$$

which does not depend on $M_T$ and may not be larger than (11).

– If all attackers wait, the attackers’ expected aggregate reward equals 0 and is less than (11).

To prevent attacks in this state, high value of $C_b$ should be set to make (11) larger than (31).

2) $(\sum_{i \in N \backslash M} D_i = 0, \sum_{i \in M} D_i = \bar{M} \geq 1)$: The attackers may report truthfully or falsely in Phase I:

- If all attackers report 0 in Phase I, then the announcement at the fusion center is $H_0$ (idle), and all honest SUs will transmit. It is easy to check that all attackers will transmit and their expected aggregate reward is given by (15) which is negative.

- If some attackers report 1 in Phase I, then the announcement at the fusion center is $H_1$ (busy), and all honest SUs will not transmit.

  – If some attackers with number $1 \leq M_T \leq M$ choose to transmit, the attackers’ expected aggregate reward is:

$$R_a(s) = P_{N,\bar{M}}^I - M P_{N,\bar{M}}^B (C_p + C_b).$$

which does not depend on $M_T$ and may be negative.

– If all attackers wait, the attackers’ expected aggregate reward equals 0 which is larger than (15).

To prevent attacks in this state, high value of $C_b$ should be set to make (31) smaller than 0.

3) $(\sum_{i \in N \backslash M} D_i = K \geq 1, \sum_{i \in M} D_i = \bar{M} \in \{0, ..., M\})$: When at least one honest SU’s sensing decision is 1, then no matter what attackers report in Phase I, the fusion center always makes correct announcement $H_1$ (busy). All honest SUs will not transmit in Phase II.

- If some attackers with number $1 \leq M_T \leq M$ choose to transmit in Phase II, the attackers’ expected aggregate reward is:

$$R_a(s) = P_{N,K+\bar{M}}^I - P_{N,K+\bar{M}}^B (C_p + C_b),$$

which does not depend on $M_T$ and can be positive or negative.

 - If all attackers wait in Phase II, the attackers’ expected aggregate reward equals 0.
To prevent all attacks in this state, high value of $C_b$ should be set to make (17) smaller than 0. Then we can summarize the requirement of $C_b$ to prevent attacks in all possible states in Theorem 2.

B. Relaxation of Assumptions A1 and A3

Here we will relax Assumption A1 and consider the general case where SUs have heterogeneous detection performances (i.e., different false alarm probabilities $P_f$ and missed detection probabilities $P_m$) and transmission rates. We are interested to know whether our attack-prevention mechanisms (with some minor modification of system parameters) can still apply, and how to change punishments to attackers. Due to the page limit, we only examine the direct punishment here. The effectiveness of the indirect punishment can be shown similarly.

Observation 1 in Section V showed that the single attacker scenario ($M = 1$) is the most challenging attack scenario for the direct punishment mechanism. Thus we will focus on the single attacker scenario to check the effectiveness of this mechanism. We label the attacker as the $N$th SU, and we denote its false alarm probability and missed detection probability as $P_{f,A}$ and $P_{m,A}$, respectively. For the ease of analysis, we still consider all honest SUs having the same $P_f$ and $P_m$.

We denote the attacker’s transmission rate as $r_A$, and an honest SU $i < N$ has a different transmission rate $r_i$. When all SUs share the same transmission opportunity using TDMA mode, the attacker obtains a data rate of $r_A/N$.

First of all, we need to change the two notations in (5) and (6) as follows. When $0 \leq k \leq N-1$, honest SUs sense the channel busy ($\sum_{i=1}^{N-1} D_i = k$) and the attacker senses idle ($D_N = 0$). The condition probability that the channel is actually idle is

$$P_{I|N,(k)+0} = Pr\left(\text{idle} \mid \sum_{i=1}^{N-1} D_i = k, D_N = 0\right)$$

$$= \frac{P_f(1 - P_f)^{N-1-k}P_f^k(1 - P_{f,A})}{P_f(1 - P_f)^{N-1-k}P_f^k(1 - P_{f,A}) + (1 - P_f)(1 - P_m)^kP_m^{N-1-k}P_{m,A}}. \quad (34)$$

15If we consider different detection performances for honest SUs, the analysis becomes more complicated without adding more meaningful insights. Intuitively, as honest SUs’ overall detection performance becomes more precise, the attacker can predict the channel state more precisely by overhearing honest SUs’ reports.
The conditional probability that the channel is actually busy is

\[ P_{B,N,(k)+(0)}^I = 1 - P_{N,(k)+(0)}. \]  

(35)

When \( 0 \leq k \leq N - 1 \), honest SUs sense the channel busy \( \left( \sum_{i=1}^{N-1} D_i = k \right) \) and the attacker also senses busy \( (D_N = 1) \). The conditional idle and busy probabilities are respectively

\[ P_{N,(k)+(1)}^I = Pr\left( \text{idle} \left| \sum_{i=1}^{N-1} D_i = k, D_N = 1 \right. \right) \]

\[ = \frac{P_I(1 - P_I)^{N-1-k}P_f^k P_{f,A} N - 1}{P_I(1 - P_I)^{N-1-k}P_f^k P_{f,A} + (1 - P_I)(1 - P_m)^k P_m^{N-1-k}(1 - P_{m,A})}; \]

(36)

and

\[ P_{B,N,(k)+(1)}^I = 1 - P_{N,(k)+(1)}. \]

(37)

With the help of above notations, we can similarly analyze how the direct punishment works and how to determine the punishment as in Section \( \text{V} \)

**Theorem 4:** For the single attacker in the network, there exists a threshold

\[ C_{b}^{th} = \frac{P_I}{1 - P_I} \left( \frac{1 - P_I}{P_m} \right)^{N-1} \frac{1 - P_{f,A}}{P_{m,A}} \frac{N - 1}{N} r_A, \]

(38)

such that any value \( C_{b} > C_{b}^{th} \) can prevent all attack scenarios described in Section \( \text{IV} \).

**Proof.** By examining different possible states as in Section \( \text{IV} \) we can derive the attacker’s optimal behavior. Then in response to the attacker’s optimal behavior, we find the proper value of direct punishment \( C_{b} \) to prevent all attacks.

1) **State** \( s = \left( \sum_{i=1}^{N-1} D_i = 0, D_N = 0 \right) \): When the sensing results are all 0, then the attackers may report truthfully or falsely in the Phase I:

- If the attacker reports 0 in Phase I, then the announcement at the fusion center is \( \mathcal{H}_0 \) (idle), and all honest SUs will transmit. It is easy to check that the attacker will also transmit and receive a positive expected reward

\[ R_A(s) = \frac{P_I}{N} - P_{B,N,(0)+(0)} C_{p} > 0, \]

(39)

which is similar to (3).

- If the attacker reports 1 in Phase I, then the announcement at the fusion center is \( \mathcal{H}_1 \) (busy) and all honest SUs will not transmit.

  - If the attacker chooses to transmit, its expected reward is

\[ R_A(s) = P_{N,(0)+(0)} r_A - P_{B,N,(0)+(0)}(C_p + C_{b}), \]

(40)
which may or may not be larger than (39).

- If the attacker waits, its expected reward equals 0 and is less than (39).

To prevent attacks in this state, a high value of $C_b$ should be set to make (39) larger than (40). In other words,

$$C_b > \frac{P_I (1 - P_{f,A})}{(1 - P_I) P_{m,A}} \left( \frac{1 - P_f}{P_m} \right)^{N-1} \frac{N - 1}{N} r_A,$$

where we denote the term in the right-hand side as threshold $C_{b \text{th}1}$. It is easy to check that $C_{b \text{th}1}$ is decreasing in both $P_{f,A}$ and $P_{m,A}$, but is increasing in $P_I$, $N$, and $r_A$.

2) State $s = \left( \sum_{i=1}^{N-1} D_i = 0, D_N = 1 \right)$: The attacker may report truthfully or falsely in Phase I:

- If the attacker reports 0 in Phase I, then the announcement at the fusion center is $\mathcal{H}_0$ (idle), and all honest SUs will transmit. It is easy to check that the attacker will also transmit and its expected reward is

$$R_A(s) = P_{N,(0)+(1)}^I r_A - P_{N,(0)+(1)}^B (C_p + C_b),$$

which is negative as required by the optimality of OR-rule.

- If the attacker reports 1 in Phase I, then the announcement at the fusion center is $\mathcal{H}_1$ (busy), and all honest SUs will not transmit.

  - If the attacker chooses to transmit, its expected reward is

$$R_A(s) = P_{N,(0)+(1)}^I r_A - P_{N,(0)+(1)}^B (C_p + C_b),$$

  which may or may not be negative.

  - If the attacker waits, its expected reward equals 0 which is larger than (42).

To prevent attacks in this state, a high value of $C_b$ should be set to make (43) smaller than 0. This gives to

$$C_b > \frac{P_I P_{f,A}}{(1 - P_I)(1 - P_{m,A})} \left( \frac{1 - P_f}{P_m} \right)^{N-1} r_A - C_p,$$

where we denote the term in the right-hand side as threshold $C_{b \text{th}2}$.

3) State $s = \left( \sum_{i=1}^{N-1} D_i = K \geq 1, D_N = M \in \{0,1\} \right)$: When at least one honest SU’s sensing decision is 1, then no matter what the attacker reports in Phase I, the fusion center always makes correct announcement $\mathcal{H}_1$ (busy). All honest SUs will not transmit in Phase II.

- If the attacker chooses to transmit in Phase II, its expected reward is

$$R_A(s) = P_{N,(K)+(\bar{M})}^I r_A - P_{N,(K)+(\bar{M})}^B (C_p + C_b),$$

where

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which may be positive or negative.

- If the attacker waits in Phase II, its expected reward equals 0.

To prevent all attacks in this state, a high value of $C_b$ should be set to make $C_b > 0$. This gives to

$$C_b > \frac{P_I}{1 - P_I} \left( \frac{1 - P_I}{P_m} \right)^{N-1} \left( \frac{P_I P_m}{(1 - P_I)(1 - P_m)} \right)^K \left( \frac{1 - P_{f,A}}{1 - P_{m,A}} \right)^{1-\bar{M}} \left( \frac{P_{f,A}}{1 - P_{m,A}} \right)^{\bar{M}} r_A - C_p,$$

which is maximized when $K = 1$ and $\bar{M} = 0$ due to $P_m < 0.1$ and $P_I < 0.1$ as explained in footnote 13. To prevent all attacks in this state, we should require

$$C_b > \frac{P_I}{1 - P_I} \left( \frac{1 - P_I}{P_m} \right)^{N-1} \left( \frac{P_I P_m}{(1 - P_I)(1 - P_m)} \right) \frac{1 - P_{f,A}}{P_{m,A}} r_A - C_p,$$

where the right-hand side is denoted as threshold $C_b^{th3}$.

To summarize, the requirement of $C_b$ to prevent attacks is $C_b > \max(C_b^{th1}, C_b^{th2}, C_b^{th3})$ in all possible states. It is easy to check that $C_b^{th1} > C_b^{th2}$ and $C_b^{th1} > C_b^{th3}$, and we can conclude the results in Theorem 4.

Observation 5: $C_b^{th}$ is increasing in both idle probability $P_I$ and the number of honest SUs $N - 1$.

A larger $P_I$ means a higher channel availability, and thus encourages the attacker to launch an attack so that it can exclusively utilize the channel more frequently. Also, as the honest SU number $N - 1$ increases, the more honest SUs’ sensing reports are overheard by the attacker. The attacker can estimate the actual channel state more accurately, and it is more likely to launch an attack.

Observation 6: Threshold $C_b^{th}$ is increasing in the attacker’s rate $r_A$, and it is decreasing in the attacker’s false alarm probability $P_{f,A}$ and missed detection probability $P_{m,A}$.

As the attacker’s rate $r_A$ increases, it values the exclusive transmission opportunity more. The attacker has a higher incentive to attack, and a higher $C_b^{th}$ is required to prevent the attack.

Figure 7 shows the threshold $C_b^{th}$ as a function of the attacker’s false alarm probability $P_{f,A}$ and missed detection probability $P_{m,A}$. Intuitively, as $P_{f,A}$ increases, the attacker has higher probability to overlook the channel access opportunity and it has less incentive to launch an attack. As $P_{m,A}$ increases, the attacker has a higher probability to trigger direct punishment and thus it is more conservative to attack. In both cases, the fusion center can announce a lower $C_b$ to prevent all attacks.
Fig. 7. Direct punishment threshold $C_{th}^{th}$ for different $P_{f,A}$ and $P_{m,A}$ with $(P_f, P_m, N) = (0.05, 0.05, 11).

C. Attack Prevention in Case AT of Section VI

Section VI focuses on Case NT. Here we discuss Case AT with multiple attackers ($M \geq 1$). Table III in Section IV shows that with no punishment, the attacker may still obtain a positive reward by transmission even when at least one SU senses the channel busy in Case AT. Next, we discuss the attacker’s action $u(s)$ under any given state $s = (\sum_{i \in N \setminus M} D_i, \sum_{i \in M} D_i, \text{Punishment})$.

- **State $s = (\sum_{i \in N \setminus M} D_i, \sum_{i \in M} D_i = K, \text{off})$:** Before the indirect punishment is triggered, the attackers may purposely change their attack behaviors (comparing to the actions in Table II in Section IV) in some states to deter punishment.

- **State $s = (0, 0, \text{off})$:** at least one attacker still chooses the action (busy, transmit) as in Table III. In this state, the attackers obtain the largest expected aggregate reward $P_{N,0}^f - MP_{N,0}^B C_p$ and induces the smallest missed detection probability $P_{N,0}^B$ to trigger punishment.

- **State $s = (\sum_{i \in N \setminus M} D_i \geq 0, \sum_{i \in M} D_i \geq 0, \text{off})$:** the attackers may choose not to attack even if they can obtain a positive expected aggregate reward in current time slot, which is different from no punishment scenario in Table III. This is because that the attackers fear to trigger the long-term indirect punishment, and they will attack only when missed detection probability to trigger punishment is low with small $\sum_{i \in N} D_i$.

- **State $s = (\text{Unknown}, \sum_{i \in M} D_i = K, \text{on})$:** After the indirect punishment is triggered, the
attackers know their own sensing results and will choose the actions as follows.

- **Weak Cooperation (Case WC):** the attackers will choose the action (N/A, wait) even if all attackers sense the channel idle. Otherwise, they will receive a negative expected aggregate reward $P^I_{M,K} - M P^B_{M,K} C_p$.

- **Strong Cooperation (Case SC):** the attackers will choose the action (N/A, transmit) when all attackers sense the channel idle. Even if at least one attacker senses the channel busy, they will still choose the action (N/A, transmit) if $P^I_{M,K} \geq M P^B_{M,K} C_p$.

*Lemma 2:* The attackers’ optimal long-term expected aggregate rewards in Case WC and Case SC are

$$LR^H_{WC} = LR^H_{SC} = \frac{M}{1 - \delta} \Pr \left( \sum_{i \in \mathcal{N}} D_i = 0 \right) \left( P^I_{N,0} - \frac{1}{N} P^B_{N,0} C_p \right),$$  \hspace{1cm} (48)

by behaving honestly, and

$$LR^{DH}_{WC} = \max_{0 \leq z \leq N} \sum_{k=0}^{z} \Pr \left( \sum_{i \in \mathcal{N}} D_i = k \right) \left[ \frac{P^I_{N,k} - M P^B_{N,k} C_p}{1 - \delta \left( 1 - \sum_{k=0}^{z} \Pr \left( \sum_{i \in \mathcal{N}} D_i = k \right) \right) P^B_{N,k} \right]$$

$$LR^{DH}_{SC} = \max_{0 \leq z \leq N} \sum_{k=0}^{z} \Pr \left( \sum_{i \in \mathcal{N}} D_i = k \right) \left\{ \frac{P^I_{M,K} - M P^B_{M,K} C_p}{1 - \delta \left( 1 - \sum_{k=0}^{z} \Pr \left( \sum_{i \in \mathcal{N}} D_i = k \right) \right) P^B_{M,K} \} + \frac{\delta}{1 - \delta \left( 1 - \sum_{k=0}^{z} \Pr \left( \sum_{i \in \mathcal{N}} D_i = k \right) \right) P^B_{N,K} \right\},$$  \hspace{1cm} (50)

by behaving dishonestly. Here the superscript “$H$” indicates honest behaviors of attackers and “$DH$” indicates dishonest behaviors. We denote the value of $z$ that achieves the maximum of (49) in Case WC or (50) in Case SC as $z^*$. The attackers’ optimal policy $u^*$ has a threshold structure as follows.

- If $\sum_{i \in \mathcal{N}} D_i \leq z^*$: At least one attacker will take the action (busy, transmit) before the indirect punishment is triggered. After the indirect punishment is triggered,
  - Case WC: all attackers will take the action (N/A, wait).
  - Case SC: all attackers will take the action (N/A, transmit) if $P^I_{M,K} > M P^B_{M,K} C_p$ where $K$ attackers sense the channel busy. Otherwise, they will take the action (N/A, wait).

- If $\sum_{i \in \mathcal{N}} D_i > z^*$: The attackers will take the action (busy, wait) before indirect punishment is triggered. After the indirect punishment is triggered,
  - Case WC: all attackers will take the action (N/A, wait).
– Case SC: all attackers will take the action (N/A, transmit) if \( P_{M,K}^I > MP_{M,K}^B C_p \) where \( K \) attackers sense the channel busy. Otherwise, they will take the action (N/A, wait).

We can show in Lemma 2 that \( LR_{WC}^{DH} < LR_{WC}^H \) in Case WC and \( LR_{SC}^{DH} < LR_{SC}^H \) in Case SC when \( \delta \) is close to 1. Thus we can find an appropriate discount factor threshold to ensure that \( LR_{WC}^{DH} < LR_{WC}^H \) for Case WC and \( LR_{SC}^{DH} < LR_{SC}^H \) for Case SC.

**Theorem 5:** For multiple attackers in Case AT, there exists a threshold \( \delta^th \in (0, 1) \) such that no attacks will happen if \( \delta > \delta^th \).

D. Proof of Lemma 2

In Case NT, the attackers will only attack with the action (busy, transmit) when all SUs sense the channel idle when the indirect punishment is not triggered. But they may or may not transmit after the punishment is triggered.

1) Case WC (Weak Cooperation): In Case WC, the attackers will not transmit even when all attackers sense the channel idle after the punishment is triggered.

If the attackers behave as honest SUs, the indirect punishment will never be triggered. They share the spectrum opportunities with the honest SUs when all SUs sense the channel idle. The attackers’ long-term expected aggregate reward is

\[
LR_{WC}^H = \sum_{t=0}^{\infty} \delta^t Pr \left( \sum_{i \in N} D_i = 0 \right) \left( P_{N,0}^I \frac{1}{N} - P_{N,0}^B C_p \right) M,
\]

which can be rewritten as in (26).

If the attackers attack with the action (busy, transmit) when all SUs sense the channel idle \( (\sum_{i \in N} D_i = 0) \), then in time slot \( t = 0 \) the indirect punishment will be triggered with the missed detection probability \( P_{N,0}^B \). If no collision happens with the probability \( P_{N,0}^I \), the attack will not be detected and the attackers will attack again if all SUs sense the channel idle in the next time slot. By focusing on time slot \( t = 0 \), the attackers’ long-term expected aggregate reward is

\[
LR_{WC}^{DH} = Pr \left( \sum_{i \in N} D_i > 0 \right) \delta LR_{WC}^{DH} + Pr \left( \sum_{i \in N} D_i = 0 \right) \left[ P_{N,0}^I \left( 1 + \delta LR_{WC}^{DH} \right) - P_{N,0}^B (MC_p) \right].
\]

We can then recursively rewrite \( LR_{WC}^{DH} \) as in (27).

2) Case SC (Strong Cooperation): In Case SC, the attackers will still transmit when all attackers sense the channel idle after the punishment is triggered.
If the attackers behave as honest SUs, no indirect punishment will be triggered and they will receive the same long-term expected aggregate reward in (26).

If the attackers attack with the action (busy, transmit) when all SUs sense the channel idle in time slot $t = 0$, we can derive the attackers’ long-term expected aggregate reward similar as the Case$\text{WC}$,

$$LR_{SC}^{DH} = Pr \left( \sum_{i \in N} D_i > 0 \right) \delta LR_{SC}^{DH} + Pr \left( \sum_{i \in N} D_i = 0 \right)$$

$$\cdot \left[ P_{N,0}^{I} (1 + \delta LR_{SC}^{DH}) - P_{N,0}^{B} MC_p + P_{N,0}^{B} \frac{\delta}{1 - \delta} Pr \left( \sum_{i \in M} D_i = 0 \right) (P_{M,0}^{I} - MP_{M,0}^{B} C_p) \right].$$

The only difference here is that the attackers can still obtain a positive expected aggregate reward after the punishment is triggered. Then we can recursively rewrite $LR_{SC}^{DH}$ as in (28).

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