Defending Against Stealthy Attacks on Multiple Nodes with Limited Resources: A Game-Theoretic Analysis

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Abstract—Stealthy attacks have become a major threat for cyber security. Previous works in this direction fail to capture the practical resource constraints and mainly focus on one-node settings. In this paper, we propose a two-player game-theoretic model including a system of multiple independent nodes, a stealthy attacker and an observable defender. In our model, the attacker can fully observe the defender’s behavior and the system state, while the defender has zero feedback information. Further, a strict resource constraint is introduced to limit the frequency of the attacks/defenses for both players. We characterize the best responses for both attacker and defender under both non-adaptive and adaptive strategies. We then study the sequential game where the defender first announces its strategy and the attacker then responds accordingly. We have designed an algorithm that finds a nearly optimal strategy for the defender and provided a full analysis of its complexity and performance guarantee.

Index Terms—Stealthy Attacks, Resource Constraints, Game Theory

I. INTRODUCTION

Increasingly sophisticated cyber attacks constantly push the evolution of cyber security. In recent years, worldwide organizations and IT companies, e.g., United Nation, Google and Amazon, are facing a significantly increasing number of Advanced Persistent Threats (APT) [8]. The APT attack has several distinguishing properties that render traditional defense mechanisms less effective. First, they are often launched by incentive driven entities, including government and competitive companies with specific targets. Second, the APT attack is persistent, which usually involves multiple stages and frequent compromises of the system. Based on [1], half of the entities suffering APT attacks experienced another successful compromise within one year. Third, they are highly adaptive and stealthy, often operating in a “low-and-slow” fashion [15] in order to maintain a small footprint and avoid being detected. In fact, some of the past APT attacks have been so effective because they have gone undetected for months or longer [9], [14]. Hence, conventional security measures against one-shot attack and known attack types are not sufficient in the face of long-lasting and stealthy attacks. Meanwhile, the objective of APT attacks usually includes the key information theft and complete control over the system, resulting in a much bigger loss than traditional cyber attacks.

In this paper, we study a two-player non-zero-sum game that explicitly models stealthy attacks with resource constraints, as an extension of the asymmetric version of the FlipIt game considered in [22]. We consider a system with $N$ independent nodes (or components), an attacker, and a defender. Both players compete for the control of the system by attacking or defending each node, subject to an instantaneous move cost per node and a long-term average resource constraint across the entire system. The attacker tries to maximize its benefits by successfully compromising nodes, and the defender aims at minimizing the total defense cost and value loss incurred by losing control of a node.

To model the stealthy attacks, we assume that the defender has no feedback about the node state and the attacker’s behavior across the entire game, which is reasonable in many security setups. On the other hand, the attacker is capable of observing the defender’s each move as well as the node state, and makes decisions accordingly. In this work, we consider two commonly adopted solution concepts, Nash Equilibrium and Sequential Equilibrium, both of which have been applied to cybersecurity. In the former, the defender and the attacker determine their strategies at the beginning of the game simultaneously, while in the latter, the defender acts as the leader of the game and commits to a strategy first, and the attacker as the follower then responds accordingly.

For tractability and simplifying the analysis, we assume that the set of nodes are independent in the sense that the proper functioning of one node does not depend on other nodes, which serves as a first-order approximation of the more general setting of interdependent nodes to be considered in our future work. Despite of the assumption that each node is independent, the multi-node setting together with the resource constraints impose significant challenges in characterizing the best responses, Nash Equilibria and Sequential Equilibria of the games.

One example where our game model can be applied is key rotation. For a system with multiple communication links or servers that are protected by different keys, an APT attacker may compromise some of the keys from time to time. A common practice is to periodically generate fresh keys by a trusted key-management service, without knowing when they are compromised. On the other hand, the attacker can easily detect when the key expires with a negligible cost and there is a constraint on the frequency of moves at both sides. There are also other examples where our model can be useful such as password reset and virtual machine refreshing [16], [22], [32].

To help reader better understand our main results, we briefly explain the key concepts below. Formal definitions can be found in Sections III and IV.
TABLE I: Main Results

<table>
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<th>Attacker</th>
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<td>(\Rightarrow) periodic defense</td>
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Nash Equilibrium: A complete characterization of NES (6 types)

Sequential Game:
- Optimal attack under a given defense strategy (16)
- A polynomial time algorithm for optimal defense (Algorithm 1)

- In a periodic defense strategy: the defender protects each node periodically. That is, the time interval between two consecutive defenses is fixed for a given node.
- In an i.i.d. attack strategy: the attacker’s waiting time before each attack (modeled as a random variable) is i.i.d. across time.
- In a Markovian defense (resp. attack) strategy: the time interval between two defenses (resp. the waiting time of each attack) follows a Markov process.
- Nearly Optimal strategy: For arbitrary small positive number \(\epsilon\), we can always find a strategy that the performance difference between this strategy and the theoretical optimal strategy is less than \(\epsilon\).

We have made following contributions in this paper with the main results summarized in Table I.

- We propose a two-player game model with multiple independent nodes, an overt defender, and a stealthy attacker where both players have strict resource constraints.
- We prove that periodic defense is a best response against i.i.d. attack among all defense strategies, and i.i.d. attack is a best response against periodic defense among all attack strategies. We further consider Markovian strategies and prove that periodic defense is still a best response against a Markovian attacking strategy, but i.i.d. attack is not necessarily a best response against a Markovian defending strategy.
- For the pair of periodic defense and i.i.d. attack strategies, we fully characterize the set of Nash Equilibria of our game, and show that there is always one (and maybe more) equilibrium, for the case when the attack times are deterministic.
- We further consider the sequential game with the defender as the leader and the attacker as the follower. We design a dynamic programming based algorithm that identifies a nearly optimal strategy (in the sense of subgame perfect equilibrium) for the defender. We also fully characterize the trade-off between algorithm performance and its complexity.

This paper is the extended version of [36]. In addition to improving the presentation and organization of the paper, we have provided in this journal submission version (i) an extension of the defender’s and attacker’s best response strategies from the non-adaptive setting to the general adaptive setting, (ii) we provide some preliminary analysis about Markovian strategies for both attacker and defender, and (iii) a better understanding of the performance vs. complexity trade-off of our algorithm for the sequential game, reducing its complexity by a factor of \(O(N^3)\) with the same performance guarantee.

The remainder of this paper is organized as follows. A summary of related work is provided in Section II. We present our game-theoretic model in Section III, and study best-response strategies of both players in Section IV. The sequential game is studied in Section VI. In Section VII, we present numerical result, and we conclude the paper in Section VIII.

II. RELATED WORK

Game theory has been extensively applied to cyber-security and network security [11], [20], [25], [31]. However, traditional models mainly focus on known attacks and largely ignore the budget constraints of both the defender and the attacker.

As mentioned in the introduction, our model is inspired by the FlipIt game [16], [32] proposed in response to an APT attack towards RSA Data Security [10], a non-zero-sum dynamic game that explicitly models the stealthy takeover of a single node. In the original model, a player obtains control over a component instantaneously by “flipping” it, and obtains feedback only when it moves. Dominant strategies or strongly dominant strategies are characterized for several classes of periodic and renewable strategies and some simple adaptive strategies. But the full analysis of Nash Equilibrium is only provided when both the defender and the attacker employ a periodic strategy with a random starting phase. Several variants of the basic model have been studied [21], [22]. In particular, a multi-node extension is considered in [21] where the attacker needs to compromise either all the nodes (AND model) or a single node (OR model) to take over a system. The authors name such a model as “FlipThem”. However, only preliminary analytic results are provided. Leslie et al. extend the “FlipThem” model in [23], [24] where the attacker can obtain partial benefits by compromising a certain number (larger than a threshold) of nodes. An asymmetric model similar to ours where the attacker is stealthy while the defender is observable is considered in [22], where full Nash Equilibrium analysis is provided but only for the single node setting. In [28], Nochenson et al. first initiate the effort of adding player’s characterization information including gender and age in the FlipIt game model. Basak et al. [13] further extend the concept by adding different type of rationale of human agents. In [37], Zheng et al. use multi-armed bandit model to investigate the optimal timing of security updates against stealthy attacks. There are also some behavioral studies of the FlipIt game [27]. However, none of the previous works considered an explicit resource constraint on the players.

A different type of security game has also been studied in the literature mainly for protecting physical infrastructures [12], [19], [30], [31]. Essentially a mixed strategy Stackelberg game is considered, where the defender is the leader and the attacker is the follower. The key assumption is that the defender first decides upon a randomized defense policy, and the attacker then observes the randomized policy of the defender but not its realization before taking an action. While this is a useful assumption under certain scenarios, it may not hold when the attacker is highly adaptive. In particular, since the attacker may be able to observe the defender’s previous actions, it could take an action before the defender changes its policy to get more benefit. Moreover, the two-stage game is insufficient to capture the persistent and stealthy behaviors of advanced attacks. In spite of the fundamental differences of the two models, recent work that extend this model to multiple
defenders and bounded rationality [18], [26] provide useful insights to our model as well, which will be studied in our future work.

III. GAME MODEL

In this section, we discuss our two-player game model including its information structure, the action spaces of both attacker and defender, and their payoffs. Our game model extends the single node model in [22] to multiple nodes and includes a resource constraint on each player.

A. Basic Model

In our game-theoretic model, there are two players (the defender and the attacker) and a network of $N$ independent nodes. Each node has a value of $r_i$ representing the payoff the attacker can receive per unit time by successfully compromising node $i$. We consider finite time horizon where the game starts at time $t = 0$ and goes to any time $t = T$. We assume that time is continuous. Every time when the attacker starts an attack for node $i$, it incurs a cost of $C^A_i$ and takes a random period of time $\alpha_{i,k}$ to succeed. On the other hand, if the defender makes a move to protect node $i$, the node is immediately recovered and incurring a cost of $C^D_i$. Further, this information is immediately learned by the attacker. The attacker’s strategy is to determine $W_{i,k}$, the waiting time from the defender’s $k$-th move to its next attack on node $i$, for each $i$ and $k$. On the contrary, the defender’s strategy is to determine the time intervals between its $(k-1)$-th move and $k$-th move for each node $i$ and $k$, denoted as $X_{i,k}$. Both the attacker’s and the defender’s strategies can be randomized and adaptive in general.

In this paper, an attack strategy is considered adaptive when the attacker’s decision on $W_{i,k}$ for any $i$ and $k$ can depend on the realized value of $X_{i',k'}$ for any $i'$ and $k' \leq k$. An adaptive defense strategy is defined similarly. On the other hand, a strategy is defined as non-adaptive if the values of $W_{i,k}$’s and $X_{i,k}$’s are either pre-computed or follow fixed probability distributions. The attacker (defender) can attack (defend) multiple nodes at the same time and maintain their possession until the other player’s next move, which may or may not change the node state.

In addition to the move cost, we introduce a strict resource constraint for each player, which is a practical assumption but has been ignored in most prior works on security games. In particular, we place an upper bound on the average amount of resource that is available to each player at any time (to be formally defined below). As in typical security games, we assume that $r_i, C^A_i, C^D_i$ are the distribution of $\alpha_{i,k}$, and the budget constraints are all common knowledge of the game, that is, they are known to both players. Without loss of generality, all nodes are assumed to be protected at time $t = 0$. Table II summarizes the notations used in the paper.

As in [22], we consider an asymmetric feedback model where the attacker’s moves are stealthy, while the defenders’ moves are observable. More specifically, at any time, the attacker knows the full history of moves by the defender, as well as the state of each node, while the defender does not know whether a node is compromised or not. This asymmetric information structure is crucial in modeling stealthy attacks in cyber security.

B. Defender’s Problem

We model the total cost to the defender as the summation of the total time when nodes are compromised and the total move cost. The defender aims at maximizing its payoff, which is defined as the negation of its total loss. Given the attacker’s strategy $\{W_{i,k}\}$, the defender faces the following optimization problem:

$$\max_{\{X_{i,k}\}, L_i} \mathbb{E} \left[ \sum_{i=1}^{N} \left( \frac{\left( T - \sum_{k=1}^{L_i} \min(W_{i,k} + \alpha_{i,k}, X_{i,k}) \right) - L_i C^D_i}{T} \right) \right]$$

and the optimization variable $X_{i,k}$ and $L_i$ satisfy the following two constraints.

$$\sum_{i=1}^{N} \frac{L_i}{T} \leq B \text{ with probability 1}$$

$$\sum_{k=1}^{L_i} X_{i,k} \leq T \text{ with probability 1 } \forall i$$

where $L_i$ (a random variable) is the total number of defense applied to node $i$ during time $T$. In (1), $T - \sum_{k=1}^{L_i} \min(W_{i,k} + \alpha_{i,k}, X_{i,k})$ refers to the total time when node $i$ is compromised and $L_i C^D_i$ is the overall move cost. The first constraint defines an upper bound $B$ of the average number of nodes that can be protected at any time. The second constraint in (2) defines the feasible set of $X_{i,k}$.

C. Attacker’s Problem

Given the defender’s strategy $\{X_{i,k}\}$, the total cost of attacking node $i$ is then $(\sum_{k=1}^{L_i} \phi(W_{i,k}, X_{i,k})) \cdot C^A_i$, where $\phi(W_{i,k}, X_{i,k}) = 1$ if $W_{i,k} < X_{i,k}$ and $\phi(W_{i,k}, X_{i,k}) = 0$ otherwise. It is important to note that when $W_{i,k} \geq X_{i,k}$, the
The attacker actually gives up its $k$-th attack against node $i$ (this is possible as the attacker can observe when the defender moves). The attacker’s problem can be formulated as follows, where $M$ is an upper bound on the average number of nodes that the attacker can attack at any time instance.

$$\max_{W_{i,k}} \mathbb{E} \left[ \sum_{i=1}^{N} \left( T - \sum_{k=1}^{L_i} \min(W_{i,k} + \alpha_{i,k}, X_{i,k}) \right) \cdot r_i \right]$$

and the attacker needs to satisfy the following constraint

$$\mathbb{E} \left[ \sum_{i=1}^{N} \frac{1}{T} \int_{0}^{T} v_i(t)dt \right] \leq M$$

where $v_i(t) = 1$ if the attacker is attacking node $i$ at time $t$ and $v_i(t) = 0$ otherwise. Note that we make the assumption that the attacker has to keep consuming resources when the attack is in progress. We further have the following equation:

$$\int_{0}^{T} v_i(t)dt = \sum_{k=1}^{L_i} \left( \min(W_{i,k} + \alpha_{i,k}, X_{i,k}) - \min(W_{i,k}, X_{i,k}) \right)$$

Putting (5) into (3), (4) and moving the expectation inside, the attacker’s problem becomes

$$\max_{W_{i,k}} \sum_{i=1}^{N} \left[ T \cdot r_i - E\left[ \sum_{k=1}^{L_i} \min(W_{i,k} + \alpha_{i,k}, X_{i,k}) \right] \cdot r_i \right.$$

$$\left. - E\left[ \sum_{k=1}^{L_i} P(W_{i,k} < X_{i,k}) \right] \cdot C_i^A \right]$$

with resource constraints

$$\sum_{i=1}^{N} \left[ E\left[ \sum_{k=1}^{L_i} \left( \min(W_{i,k} + \alpha_{i,k}, X_{i,k}) - \min(W_{i,k}, X_{i,k}) \right) \right] \right] \leq M$$

### IV. BEST RESPONSES

In this section, we analyze the best-response strategies for both players. Our main result is that when the attacker employs an i.i.d. strategy, a periodic strategy is a best response for the defender, and vice versa. To prove this result, however, we have provided characterization of best responses in more general settings.

#### A. Defender’s Best Response

We first show that an optimal deterministic defense strategy is always optimal in general for (1). We then prove that the periodic defense is optimal against i.i.d. attacks.

**Lemma IV.1.** Suppose $x_{i,k}^*$ and $l_{i,k}^*$ are the optimal solutions of (1) among all deterministic strategies, then they are also optimal among all the strategies (including both adaptive and non-adaptive strategies).

**Proof sketch:** For a general defense strategy $X_{i,k}$, we can achieve the same expected payoff for defender by assigning $X_{i,k} = x_{i,k}^*$ with probability 1 and the same for $L_i$. Thus, the deterministic strategy is also optimal among all random strategies. For detailed proof, please see [35].

According to the lemma, it suffices to consider defender’s strategies where both $X_{i,k}$ and $L_i$ are deterministic. It is also worth mentioning that the order in which nodes are defended makes no difference since the nodes are independent of each other. We then define the set of i.i.d. attack strategies and show that periodic defense is a best response against i.i.d. attacks.

**Definition IV.1.** An attack strategy is called i.i.d. if it is non-adaptive, and $W_{i,k}$ is independent across $i$ and is i.i.d. across $k$.

**Theorem IV.1.** Periodic defense is a best response among all defense strategies if the attacker employs an i.i.d. strategy.

To prove this result, we need the following definition.

**Definition IV.2.** For a given $L_i$, we define a set $X_i$ that includes all deterministic defense strategies for node $i$ with the following properties:

1. $\sum_{i=1}^{L_i} X_{i,k} = T_i$;
2. $F_{W_{i,k} + \alpha_{i,k}}(X_{i,k}) = F_{W_{i,k} + \alpha_{i,k}}(X_{i,k})$ for all $k, j$,

where $F_{W_{i,k} + \alpha_{i,k}}(\cdot)$ is the marginal CDF of $W_{i,k} + \alpha_{i,k}$. Let $X_i$ denote the set of defense strategies where for each node $i$, a strategy in $X_i$ is adopted.

Note that (1) $X_i$ can be an empty set in general due to the randomness of $W_{i,k} + \alpha_{i,k}$; (2) for deterministic $X_{i,k}$, $W_{i,k}$ is independent of any $X_{k',\tau}$ s.t. $T_{j}(\tau) \geq T_i(k)$. The following lemma shows that when $X_i$ is non-empty for all $i$, any strategy that belongs to $X_i$ is a defender’s best deterministic strategy against a non-adaptive attacker.

**Lemma IV.2.** Consider a non-adaptive attack strategy. For any given set of $\{L_i\}$ with $\sum_{i=1}^{N} \frac{L_i}{T} \leq B$, if $X_i \neq \emptyset$ for any $i$, then any strategy in $X_i$ is a best deterministic strategy for the defender.

**Proof.** We first define the defender’s payoff for node $i$ as

$$U_i^D(X_{i,k}, L_i) = \frac{-\left( T - \sum_{k=1}^{L_i} E\left[ \min(W_{i,k} + \alpha_{i,k}, X_{i,k}) \right] \right) \cdot r_i}{T}$$

...
Since \( \{L_i\} \) are fixed, Problem (1) can be divided into \( N \) independent sub-problems as follows:

\[
\max_{X_{i,k}} U^D_i(X_{i,k}) \quad \text{s.t.} \quad \sum_{k=1}^{L_i} X_{i,k} \leq T \tag{9}
\]

We first assume that \( F_{W_{i,k} + \alpha_{i,k}}(X_{i,k}) \) is continuous for any \( i \) and \( k \). Since the attacking strategy is non-adaptive, \( X_{i,k} \) is independent of \( W_{i,k} \). We can then prove that the objective function is concave by showing that the Hessian matrix of \( U^D_i((X_{i,k})) \) with respect to \( X_{i,k},(1 \leq k \leq L_i) \) is negative semi-definite. We note that even when \( F_{W_{i,k} + \alpha_{i,k}}(X_{i,k}) \) is not continuous, the concavity can still be proved using the subgradient concept. The details are omitted to save space.

Since \( U^D_i(X_{i,k}) \) is concave and continuously differentiable, the KKT conditions are both sufficient and necessary. From the KKT conditions, we have \( \nu^\ast \left( \sum_{k=1}^{L_i} X_{i,k} - T \right) = 0 \) and \( F_{W_{i,k} + \alpha_{i,k}}(X_{i,k}) = F_{W_{i,k} + \alpha_{i,k}}(X_{i,j}) \) \( \forall j,k \), where \( \nu^\ast \) is the Lagrangian multiplier. It is clear that \( U^D_i(X_{i,k}) \) is maximized when the constraint is tight, that is, \( \sum_{k=1}^{L_i} X_{i,k} = T \). Note that there may exists a set of \( X_{i,k} \) with \( \sum_{k=1}^{L_i} X_{i,k} < T \) that is also optimal for (9). Thus, the two conditions in Definition IV.2 are sufficient but not necessary.

We now prove Theorem IV.1.

**Proof.** For any fixed \( \{L_i\} \), let \( X_i \triangleq \left[ \frac{T}{L_i} \frac{T}{L_i} \cdots \frac{T}{L_i} \right] \). It is easy to check that \( \{X_i\} \) satisfies the fist property in Definition IV.2 and will satisfy the second property if \( \alpha_{i,k} \) is i.i.d. with respect to \( k \). According to Lemma IV.2, \( \{X_i\} \) is an optimal (deterministic) solution given \( \{L_i\} \). It follows that if we let \( \{L_i^\ast\} \) denote the optimal solution of

\[
\max_{L_i} \sum_{i=1}^{N} \left( T - \sum_{k=1}^{L_i} E[\min(W_{i,k} + \alpha_{i,k}, \frac{T}{L_i})] \right) \cdot r_i - L_i C^D_i
\]

with resource constraint \( \sum_{i=1}^{N} L_i^\ast \leq B \). Then \( X_i^\ast \triangleq \left[ \frac{T}{L_i^\ast} \frac{T}{L_i^\ast} \cdots \frac{T}{L_i^\ast} \right] \) is an optimal solution to the defender’s problem. Hence, a periodic strategy with periods of \( X_i^\ast \) for all \( i \) is a best-response strategy for the defender.

According to Theorem IV.1, the defender use periodic strategy to keep the system stable, in the sense of the same total loss between two defenses. Since the distribution of attacker’s waiting time \( W_{i,k} \) does not change with time, a fixed defense interval provides the same expected payoff between every two consecutive moves. Moreover, the convexity of the defender’s optimization problem guarantees an optimal solution under a given attack strategy.

### B. Attacker’s Best Response

We first analyze the attacker’s best response against any deterministic defense strategy, then show that the i.i.d. strategy is the best response against periodic defense.

**Definition IV.3.** An attack strategy is called independent non-adaptive if it is non-adaptive, and \( W_{i,k} \) is independent across \( i \) and \( k \).

**Lemma IV.3.** When the defense strategy is deterministic, for any attacking strategy (adaptive or non-adaptive), there always exists an independent non-adaptive strategy that gives the attacker the same payoff.

**Proof.** When the defense strategies are deterministic, we can move the expectation in (6) after the summation over \( k \) and the expectation is with respect to \( \alpha_{i,k} \). The same for constraint (7). Then, the proof is done as long as we can construct an independent non-adaptive strategy \( W^\prime_{i,k} \) such that for all \( i \) and \( k \), we have

1. \( E[\min(W_{i,k} + \alpha_{i,k}, X_{i,k})] = E[\min(W^\prime_{i,k} + \alpha_{i,k}, X_{i,k})] \)
2. \( E[\min(W_{i,k}, X_{i,k})] = E[\min(W^\prime_{i,k}, X_{i,k})] \)
3. \( P(W^\prime_{i,k} < X_{i,k}) = P(W^\prime_{i,k} < X_{i,k}) \)

Since \( X_{i,k} \) is deterministic and \( \alpha_{i,k} \) is independent across \( i \) and \( k \), the expectation above is with respect to the marginal distribution of \( W_{i,k} \) only. Thus, we can construct \( W^\prime_{i,k} \) whose distribution is the same as \( W_{i,k} \)’s marginal distribution which does not depend on any realization of \( X_{j,\tau} \) and \( W_{j,\tau} \) s.t. \( T_j(\tau) < T_i(\tau) \). Meanwhile, \( W^\prime_{i,k} \) is independent across \( i \) and \( k \).

According to Lemma IV.3, it suffices to consider independent non-adaptive strategies when the defender uses deterministic strategies.

**Lemma IV.4.** When the defense strategy is deterministic, the attacker’s best response (among non-adaptive strategies) must satisfy the following condition

\[
W^\ast_{i,k} = \begin{cases} 0 & w.p. \frac{w.p.}{w.p.} \frac{w.p.}{1 - p_{i,k}} \end{cases} \tag{10}
\]

Please find the proof in Section IX-A. Lemma IV.4 implies that for each node \( i \), the attacker’s best strategy is to either attack node \( i \) immediately after it realizes the node’s recovery, or gives up the attack until the defender’s next move. There is no incentive for the attacker to wait a small amount of time to attack a node before the defender’s next move. The constraint \( M \) actually determines the probability that the attacker will attack immediately. If \( M \) is large enough, the attacker will never wait after defender’s each move. We then find the attacker’s best response when the defender employs the periodic strategy.

**Theorem IV.2.** Assume that for any \( i \), the attacking times \( \alpha_{i,k} \)’s are i.i.d. across \( k \). When the defender employs a periodic strategy, the i.i.d. strategy is the attacker’s best response among all strategies.

**Proof.** Suppose that the defender uses a periodic strategy where for any \( i \), \( X_{i,k} = 1/m_i \) for any \( k \). With (10), the attacker’s problem (6) can be simplified to a fractional knapsack problem with decision variables \( \{p_{i,k}\} \). For any given node \( i \), \( p_{i,k} \)’s unit reward (payoff in the target function divided by weight in the constraint) across \( k \) are all equal when \( \alpha_{i,k} \)’s are i.i.d. across \( k \). Thus, setting all the \( p_{i,k} \) in (10) equal is one of the optimal solution. Therefore, the i.i.d. strategy is a best solution for attacker when the defender uses a periodic strategy.

### C. Simplified Optimization Problems

We put particular emphasis on the case where the defender employs a periodic strategy and the attacker uses an i.i.d. strategy.
strategy. According to Theorem IV.1 and Theorem IV.2, periodic defense and i.i.d. attack can form a pair of best-response strategies with respect to each other. Consider such pairs of strategies. Let \( m_i \triangleq \frac{L_i^i}{T} = \frac{1}{X_i} \), and let \( p_i \) denote the probability that \( W_{i,k} = 0 \) for all \( k \). We assume that all the attacking times \( \alpha_{i,k} \) are i.i.d. across \( k \) and omit the subscript \( k \) in \( \alpha_{i,k} \). The optimization problems to the defender and the attacker can then be simplified as follows.

**Defender’s problem:**

\[
\max_{m_i} \sum_{i=1}^{N} \left[ \left( E[\min(\alpha_i, \frac{1}{m_i})]p_ir_i - C_i^D \right) m_i - p_ir_i \right] 
\]

s.t. \( \sum_{i=1}^{N} m_i \leq B \)

**Attacker’s problem:**

\[
\max_{p_i} \sum_{i=1}^{N} p_i \left( r_i(1 - E[\min(\alpha_i, \frac{1}{m_i})]) \cdot m_i - C_i^A m_i \right) 
\]

s.t. \( \sum_{i=1}^{N} E[\min(\alpha_i, \frac{1}{m_i})] \cdot m_i \cdot p_i \leq M \)

We observe that the defender’s problem is a continuous convex optimization problem, while the attacker’s problem is a fractional knapsack problem. Therefore, the best response strategy of each side can be easily determined. Also, the time period \( T \) disappears in both problems. It is worth mentioning that finding the Nash Equilibrium of (11) - (12) is very challenging since the constraint of (12) is non-convex with respect to \( m_i \), thus the strategy space of this generalized Nash Equilibrium problem (GNEP) is not jointly convex.

### D. Markovian Strategies

Based on Theorems IV.1 and IV.2, the defender’s periodic strategy and attacker’s i.i.d. strategy form a Nash equilibrium among all adaptive and non-adaptive strategies. However, it remains unclear what is the best response if one of the players uses an adaptive strategy. To the best of our knowledge, there has been virtually no discussion about adaptive strategies in the field of stealthy attacks. Further, even though a deterministic strategy is always optimal for the defender based on Lemma IV.1, there may still exist non-deterministic strategies that are also optimal. Meanwhile, Nash equilibria under more general strategies from both players may exist. In this section, we provide some preliminary results in this direction by considering Markovian strategies from both the defender’s and the attacker’s perspectives. We assume that the attacker’s waiting times \( W_{i,k} \) follow (10) and define a Markovian attacking strategy as follows:

**Definition IV.4.** An attacking strategy is a Markovian strategy if the attack probabilities \( \{p_{i,k}\} \) for node \( i \) follow a discrete Markov chain over \( K \) states \( v_1, v_2, \ldots, v_K \) with transition matrix \( M^A \). That is, \( \Pr(p_{i,k+1} = v_s | p_{i,k} = v_l) = M^A(s,t) \) for any \( s \) and \( t \).

A Markovian defense strategy is defined similarly by considering \( \{X_{i,k}\} \) instead of \( \{p_{i,k}\} \). For tractability, we only consider the expected payoffs for the defender in a steady state. We show our main results about Markovian strategies in the following.

**Theorem IV.3.** If the attacker employs an ergodic Markovian strategy, the periodic strategy is defender’s best response.

The proof can be found in Section IX-B. Theorem IV.3 tells us that the defender still prefers using a periodic strategy when the attacker’s strategy space includes Markovian strategies. Consequently, the pair of periodic strategy and i.i.d. strategy naturally forms the Nash equilibrium in this case. However, the i.i.d. attack strategy may not be optimal against a Markovian defending strategy as shown in the following theorem.

**Theorem IV.4.** If the defender employs a Markovian strategy, the i.i.d. attack strategy is not optimal in general.

**Proof sketch:** The main idea is to construct a counter example where the defender uses a Markovian strategy to defend a single node and the defense interval \( X_k \) (we omit \( i \) since there is only one node) takes one of the two values \( x_1 \) and \( x_2 \). The probability of \( X_k = x_1 \) only depends on the value of \( X_{k-1} \). We then find the steady state probability of the node being compromised. The total expected payoff for the attacker can then be written in a similar form as (12) with decision variables \( p_1 \) and \( p_2 \), referring to the probabilities of launching an attack when \( X_k = x_1 \) and \( X_k = x_2 \), respectively. Since the optimal values of \( p_1 \) and \( p_2 \) for solving the knapsack problem are not equal in general, the i.i.d. attack is not optimal. A detailed proof is given in [35].

Theorem IV.4 tells us that the attacker may use an adaptive strategy against the Markovian defending strategy. Compared to the defender, since the attacker is able to observe the defending periods and the node states, the attacking strategy may become state-dependent. Therefore, Nash equilibria beyond periodic defense and i.i.d. attack can exist in the space of both adaptive and non-adaptive strategies.

### E. Discussion on Security Games in Networks

In this work, we focus on protecting a set of independent nodes where the payoff functions are additive, that is, the total payoff to a player is a weighted summation of the payoffs from each node. Even in this case, finding the equilibrium solutions of the game (11) - (12) is already very challenging as we mentioned in Section IV-C. Solving a security game in a general network setting that yields non-additive utility is even harder. Because of that, existing security game work typically assume additive utility as we did.

To extend our solutions discussed in Sections V and VI to a network setting, a promising direction is to introduce non-additive payoff functions to the defender and the attacker to capture the dependencies of node values. There are several recent work [17], [33], [34] that consider security games in network settings. In particular, Wang et al. [34] developed a general framework to convert a security game with non-additive utility to a combinatorial optimization problem over a set system, and characterized the complexity of finding the Nash Equilibrium. However, efficient algorithms are only known for some special cases and none of them apply to our setting directly. Further, most previous work on security games including [34] consider a static setting (or the steady state in a repeated setting) where the game is played only once, which cannot faithfully model the joint spatial and temporal decisions in dynamic stealthy games as we consider in this paper.
V. NASH EQUILIBRIA

In this section, we study the set of Nash Equilibria of the game where the defender employs a periodic strategy, and the attacker employs an i.i.d. strategy. For tractability, we further assume that the attacking time \( \alpha_{i,k} \) is deterministic for all \( i \) and we omit the subscript \( k \). We show that this game always has a Nash equilibrium and may have multiple equilibria of different values.

We first observe that for deterministic \( \alpha_i \), when \( m_i \geq \frac{1}{\alpha_i} \), the defender’s payoff becomes \(-m_i C_i^D\), which is maximized when \( m_i = \frac{1}{\alpha_i} \). Therefore, it suffices to consider \( m_i \leq \frac{1}{\alpha_i} \). Thus, the optimization problems to the defender (11) and the attacker employ an i.i.d. game where the defender employs a periodic strategy, and the following sets of constraints.

Any pair of strategies \((m, p)\), the payoff to the defender is

\[
U_d(m, p) = \sum_{i=1}^{N} m_i(r_i \alpha_i p_i - C_i^D) - p_i r_i
\]

s.t. \( \sum_{i=1}^{N} m_i \leq B \)

\( 0 \leq m_i \leq \frac{1}{\alpha_i}, \forall i \)

On the other hand, for a given \( m \), the attacker aims at maximizing its payoff:

\[
\max_{p_i} \sum_{i=1}^{N} p_i[r_i - m_i (r_i \alpha_i + C_i^A)]
\]

s.t. \( \sum_{i=1}^{N} m_i \alpha_i p_i \leq M \)

\( 0 \leq p_i \leq 1, \forall i \)

For a pair of strategies \((m, p)\), the payoff to the defender is

\[
U_d(m, p) = \sum_{i=1}^{N} m_i (r_i \alpha_i p_i - C_i^D) - p_i r_i
\]

while the payoff to the attacker is

\[
U_a(m, p) = \sum_{i=1}^{N} p_i[r_i - m_i (r_i \alpha_i + C_i^A)]
\]

A pair of strategies \((m^*, p^*)\) is called a (pure strategy) Nash Equilibrium (NE) if for any pair of strategies \((m, p)\), we have

\[
U_d(m, p^*) \geq U_d(m^*, p^*) \geq U_d(m^*, p)
\]

Theorem V.1. Any pair of strategies \((m, p)\) with \( F(p) = F \) and \( D(m, p) = D \) is an NE if it is a solution to one of the following sets of constraints:

1) \( \sum_{i \in F} m_i = B; \quad p^* = 0; \)
2) \( \sum_{i \in E} m_i = B; \quad p^* > 0; \quad \sum_{i \in F} m_i \alpha_i p_i = M; \)
3) \( \sum_{i \in F} m_i = B; \quad p^* > 0; \quad p_i = 1, \forall i \in F; \)
4) \( \sum_{i \in F} m_i < B; \quad p^* = 0; \quad F = F_N; \quad \rho^* = 0; \)
5) \( \sum_{i \in F} m_i < B; \quad \mu^* = 0; \quad F = F_N; \quad \rho^* > 0; \quad \rho_i = 1, \forall i \in F; \)
6) \( \sum_{i \in F} m_i < B; \quad \mu^* = 0; \quad F = F_N; \quad \rho^* > 0; \quad p_i = 1, \forall i \in F. \)

In the following, NEs that fall into each of the six cases considered above are named as Type 1 - Type 6 NEs, respectively. The next theorem shows that our game has at least one equilibrium and may have more than one NE.

Theorem V.2. The attacker-defender game always has a pure strategy Nash Equilibrium, and may have more than one NE of different payoffs to the defender.

The detailed proofs of Theorem V.1 and Theorem V.2 can be found in our technical report [35].

VI. SEQUENTIAL GAME

In this section, we study the subgame perfect equilibrium [29] of the Stuckelberg game when the defender employs a periodic strategy and the attacker employs an i.i.d. strategy. In the sequential game, the defender first commits to a strategy and makes it public, the attacker then responds accordingly. We assume that at \( t = 0 \), the leader (defender) has determined its strategy and the follower (attacker) has learned the defender’s strategy and determined its own strategy in response. In addition, the players do not change their strategies thereafter. Our objective is to identify the best sequential strategy for the defender. We adopt the same assumption in Section V and then define the subgame perfect equilibrium as follows:

Definition VI.1. A pair of strategies \((m^*, p^*)\) is a subgame perfect equilibrium of the sequential game if \( m^* \) is the optimal solution of

\[
\max_{m_i} \sum_{i=1}^{N} m_i (r_i \alpha_i p_i^* - C_i^D) - p_i^* r_i
\]

s.t. \( \sum_{i=1}^{N} m_i \leq B \)

\( 0 \leq m_i \leq \frac{1}{\alpha_i}, \forall i \)

where \( p_i^* \) is the optimal solution of

\[
\max_{p_i} \sum_{i=1}^{N} p_i[r_i - m_i (r_i \alpha_i + C_i^A)]
\]

s.t. \( \sum_{i=1}^{N} m_i \alpha_i p_i \leq M \)

\( 0 \leq p_i \leq 1, \forall i \)

Note that in a subgame perfect equilibrium, \( p_i^* \) is the optimal solution of (16), but the defender’s best strategy \( m_i^* \) is not necessarily optimal with respect to (15). Due to the multi-node setting and the resource constraints, it is challenging to identify an exact subgame perfect equilibrium strategy for the defender. We first establish several properties about the optimal defense strategy and then propose a dynamic programming based algorithm that finds a nearly optimal defense strategy.

To clearly state the properties, we partition all the nodes into four disjoint sets defined below:

1) \( F = \{i \mid m_i > 0, \quad p_i = 1\} \)
2) \( D = \{i \mid m_i > 0, \quad 0 < p_i < 1\} \)
3) \( E = \{i \mid m_i > 0, \quad p_i = 0\} \)
4) \( G = \{i \mid m_i = 0, \quad p_i = 1\} \)

We observe that the set \( D \) has at most one element since (16) is a fractional knapsack problem. Let \( \rho_i(m_i) \triangleq \frac{m_i (r_i \alpha_i + C_i^A)}{m_i \alpha_i p_i} \). We use \( m_d \) to represent \( m_i, \quad i \in D \) for simplicity and denote \( \rho_d = \rho_d(m_d) \). If \( D \) is empty, we pick any node \( i \in F \) with minimum \( \rho_i \) and treat it as a node in \( D \).

Lemma VI.1. For all optimal solutions of (15)-(16), we always have \( \rho_d \geq 0 \)

Lemma VI.2. For any given nonnegative \( \rho_d \), an optimal solution for (15)-(16) satisfies the following properties:

1) \( r_i \alpha_i - C_i^D > 0 \quad \forall i \in F \cup E \cup D \)
2) \( m_i \leq \overline{m}_i \quad \forall i \in F \)
TABLE III: Nodes in Different Sets with Given $\rho_d$

<table>
<thead>
<tr>
<th></th>
<th>$F$</th>
<th>$E$</th>
<th>$G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defender’s payoff</td>
<td>$\overline{m}_i(r_i, \alpha_i - C^D_i) - r_i$</td>
<td>$-\overline{m}_i C^D_i$</td>
<td>$-r_i$</td>
</tr>
<tr>
<td>Defender’s budget usage</td>
<td>$\overline{m}_i$</td>
<td>$\overline{m}_i$</td>
<td>0</td>
</tr>
<tr>
<td>Attacker’s budget usage</td>
<td>$\overline{m}_i$</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

3) $m_j = \overline{m}_i \forall j \in E$
4) $\overline{m}_i \leq 1/2 \forall i$
5) $B - \sum_{i \in E} \overline{m}_i - m_d > 0$.

where $\overline{m}_i = \rho_i^{-1}(\rho_d)$

**Lemma VI.3.** For any nonnegative $\rho_d$, there exists an optimal solution for (15)-(16) such that $\forall i \in F$, there is at most ONE $m_i < \overline{m}_i$ and all the other $m_i = \overline{m}_i$.

The proof of Lemma VI.3 is in Section IX-C. Lemmas 1 - VI.3 establish the foundation for the following key result about the optimal defense strategy of (15)-(16).

**Proposition VI.1.** For any nonnegative $\rho_d$, there exists an optimal solution $\{m_i\}_{i=1}^n$ such that

1) $\forall i \in F$, there is at most one $m_i < \overline{m}_i$ and all the other $m_i = \overline{m}_i$;
2) $m_d = \overline{m}_d$;
3) $\forall i \in E$, $m_i = \overline{m}_i$;
4) $\forall i \in G$, $m_i = 0$.

We denote the node whose $m_i < \overline{m}_i$ in the first property of Proposition VI.1 as node $f$ and its defending frequency as $m_f$. Based on Proposition VI.1, we can easily compute the value of $m_i$ for each node (except $m_f$) after the set allocation is fixed. Also, we can explicitly list the defender’s payoff, defender's budget usage and attacker's budget usage by putting each node into different sets as shown in Table III. For the fractional node, its $m_i$ can be computed using linear programming when all the other $m_i$ have been determined. We use dynamic programming to determine the optimal set allocation.

From the discussion above, we propose the following algorithm to the defender's problem (see Algorithm 1). The algorithm iterates over all possible node $d$ in set $D$ and all possible node $f$ with fractional assignment in set $F$. We first compute a special case when set $G$ is empty (line 2). In this case, the defender’s optimal strategy can be obtained by solving (17) based on Proposition VI.1.

$$Val(d, f) = \max_{\rho_d, \rho_f, m_f} \sum_{i \neq f} \overline{m}_i (p_i r_i \alpha_i - C^D_i) - p_i r_i + m_f (r_f \alpha_f - C^D_f) - r_f$$

s.t. $\sum_{i \neq f} \overline{m}_i + m_f \leq B$, $\sum_{i \neq f} p_i \overline{m}_i \alpha_i + m_f \alpha_f \leq M$

$$\rho_d = \frac{r_i - \overline{m}_i (r_i \alpha_i + C^A_i)}{\overline{m}_i \alpha_i} \geq 0, \quad 0 \leq p_i \leq 1, \quad m_f \geq 0 \quad (17)$$

The reason why we compute this special case first will become clear in the proof of Theorem VI.1 where we bound the performance guarantee of the algorithm. The algorithm then iterates over nonnegative $\rho_d$ with a step size $\rho_{step}$ (line 4). Given $\rho_d$, $d$, $f$, the best set allocation (together with $m_i$ for all i) are determined using dynamic programming as explained below.

For any given $\rho_d$, $d$ and $f$, we compute $\overline{m}_i$ for all $i$ (line 5). Let $SEQ(i, b, m, d, f, ind)$ denote the maximum payoff of the defender considering only node $i$ to node $i$ (excluding nodes $d$ and $f$), for a given defender’s budget $b \in [0, B]$ and an attacker’s budget $m \in [0, M]$. The parameter $ind$ is a boolean variable that indicates whether we can put nodes in set $E$ arbitrarily. If $ind$ is True, any node (except nodes $d$ and $f$) can be in set $E$. Otherwise, a node $i$ can be allocated to set $E$ only if $r_i - \overline{m}_i (r_i \alpha_i + C^D_i) \leq 0$. The value of $SEQ(i, b, m, d, f, ind)$ is determined recursively. If node $i$ is either $d$ or $f$, we simply set $SEQ(i, b, m, d, f, ind) = SEQ(i - 1, b, m, d, f, ind)$.

We have the following recurrence equation, where the three cases refer to putting node $i$ in sets $F$, $E$ and $G$, respectively.

$$SEQ(i, b, m, d, f, ind) =$$

$$\max \left\{ \begin{array}{ll}
SEQ(i - 1, b - \overline{m}_i, m - \alpha_\overline{m}_i, d, f, ind) \\
+ \overline{m}_i (r_i \alpha_i - C^D_i) - r_i \\
SEQ(i - 1, b - \overline{m}_i, m, d, f, ind) - \overline{m}_i C^D_i \\
SEQ(i - 1, b, m, d, f, ind) - r_i
\end{array} \right\} \quad (18)$$

We have the following boundary conditions:

1) The recursion $SEQ$ will return $-\infty$ when $i > 0$ and (i) $m < 0$, or (ii) $b < 0$, or (iii) $m = 0$ and $ind = False$;
2) $SEQ(0, b, m, d, f, True/False)$ returns the optimal solution of (17) when there is only one variable $m_f$. Please refer to [35] for detailed explanation.

**Algorithm 1 Sequential Strategy for Defender**

1: for $d, f \leftarrow 1$ to $n$ do
2: $\rho_{max} \leftarrow \rho : \sum_{i=1}^n \alpha_i m_i(\rho) = M$
3: for $\rho_d \leftarrow 0$ to $\rho_{max}$ with step size $\rho_{step}$ do
4: $\overline{m}_i \leftarrow m_i(\rho_d)$ for all $i$
5: $val_d'_{f, \rho_d} \leftarrow SEQ(n, B, M, d, f, True)$
6: $val_d''_{f, \rho_d} \leftarrow SEQ(n, B, M, d, f, False)$
7: $val_d'_{f, \rho_d} \leftarrow SEQ(n, B, M, d, f, True)$
8: end for
9: $P_{dp}(d, f) \leftarrow \max_{\rho_d} \{val_d'_{f, \rho_d}, val_d''_{f, \rho_d}\}$
10: end for
11: $P_{alg} \leftarrow \max_{d, f} \{P_{dp}(d, f), Val(d, f)\}$

Algorithm 1 computes the optimal solution by searching over all combinations of $d$, $f$ and $\rho_d$. For any given combination, the dynamic program actually finds all the solutions that satisfy Proposition VI.1, meaning that $P_{dp}(d, f)$ returns the optimal defense strategy under given $d$, $f$ and $\rho_d$ (line 9). Therefore, $P_{alg}$ is the maximum payoff that the defender can achieve (line 11). For the dynamic program, we round the input before running $SEQ(n, B, M, d, f, ind)$, since the recursion may never stop without rounding. Denote $\delta$ as the rounding parameter, we have $\overline{m}_i \leftarrow \lfloor \frac{\overline{m}_i}{\delta} \rfloor$, $\alpha_i \leftarrow \lfloor \frac{\alpha_i}{\delta} \rfloor$ for all $i$ and $B \leftarrow \lfloor \frac{B}{\delta} \rfloor$, $M \leftarrow \lfloor \frac{M}{\delta} \rfloor$. By setting $\delta$ small enough, Algorithm 1 can find a strategy that is arbitrarily close to the subgame perfect equilibrium strategy of the defender. Formally, we can establish the following result.

**Theorem VI.1.** Let $|P_{alg}|$ denote the defender’s cost obtained by Algorithm 1 and $|P^*|$ the optimal cost. Given $\rho_{step}$ and the
In both figures, \( r_1 = 2, r_2 = 1, w_1 = 1.7, w_2 = 1.6, C^D = 0.5, C^A = 0.6, C^1 = 1, C^2 = 1.5, B = 0.3 \) in (a), and \( M = 0.1 \) in (b).

**Corollary VI.1.** By setting both \( \rho_{\text{step}} \) and \( \delta \) with \( O\left(\frac{1}{N}\right) \), Algorithm 1 can achieve a near-optimal solution and its complexity is \( O(N^3BM) \)

**VII. NUMERICAL RESULTS**

In this section, we present numerical results for our game models. For the illustrations, we assume that all the attacking times \( \alpha_i \) are deterministic as in Sections VI. We study the payoffs of both the attacker and the defender and their strategies in both Nash Equilibrium (two-node setting) and subgame perfect equilibria (both two-node and five-node settings), and study the impact of various parameters including resource constraints \( B, M \), and the unit value \( r_1 \).

**A. Simulations with Selected Parameters**

We first study the impact of the resource constraints \( M \) and \( B \) on the player’s payoffs in a two-node setting. The results are given in Figure 2, where we have plotted both Type 1 and Type 5 NEs and subgame perfect equilibria. A Type 5 NE only occurs when \( M \) is small as shown in Figure 2a, while Type 1 NE appears when \( B \) is small as shown in Figure 2b, which is expected since \( B \) is fully utilized in a Type 1 NE while \( M \) is fully utilized in a Type 5 NE. When the defense budget \( B \) becomes large, the summation of \( m_i \) does not necessarily equal to \( B \) and thus Type 1 NEs disappear. Similarly, Type 5 NEs disappear for large attack budget \( M \). In both figures, the subgame perfect equilibria always bring the defender higher payoffs compared with Nash Equilibria, which is expected.

**B. Simulations with Real-World data**

To have a better understanding of the performance of Algorithm 1, we consider a five-node setting and use real-world data from the National Vulnerability Database (NVD) [2]. We pick five vulnerability incidents about IoT devices revealed by the database. For each incident, we use their Impact Score (the potential impact of the vulnerability), Exploitation Score (how vulnerable the thing itself is to attack), Vulnerability Base Score (how critical the vulnerability is) and Attack Complexity (Low or High) [3]–[7] as an approximation of the node value, attacking time, defending cost and attacking cost respectively. Specifically, we set node values as \( r = [5.9, 3.6, 5.9, 5.2, 3.6] \). For the attacking times, since higher Exploitation Score means easier attack, we take the reciprocal and set \( \alpha = [10/3, 9/10, 2/8, 10/2, 2/8, 10/2, 8/10, 9/10, 10] \) where the constant 10 is used for normalization. The Vulnerability Base Score is utilized to approximate the defending cost by setting \( C^D = [9.8, 6.5, 8.8, 8.1, 7.5]/3 \), while the attacking cost is set to 2 if the Attack Complexity is High and 1 otherwise. We study the effects of varying \( M \) and \( r \) in Figure 3a.

In Figure 3a, the attacker’s budget \( M \) varies from 0 to 1 and the defending budget \( B = 0.2 \). When \( M = 0 \), the defender can set \( m_i \) for all \( i \) to arbitrary small (but positive) values, so that the attacker is unable to attack any node, leading to a zero payoff for both players. As \( M \) becomes larger, the attacker’s payoff increases, while the defender’s payoff decreases, and the defender tends to defend the nodes with higher values more frequently, as shown in Figure 3a(lower). The defender gradually stop protecting low value nodes and move all the resources to defend node 3. Note that the defending frequency for node 3 is smaller than that for node 1 at the beginning. This is because when \( M \) is small, the attacker attacks each node with a very small probability, thus the defender can protect all the nodes at the same time to prevent big loss. Since node 1 and 3 have the same unit value while \( \alpha_1 < \alpha_3 \), the defender protects node 1 more frequently. However, when the attacker has enough resources to attack each node with a much higher
Algorithm 1

<table>
<thead>
<tr>
<th>No. of nodes</th>
<th>Algorithm 1</th>
<th>Algorithm 1 in [36]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>12.1 sec</td>
<td>31.4 sec</td>
</tr>
<tr>
<td>3</td>
<td>131.5 sec</td>
<td>410.8 sec</td>
</tr>
<tr>
<td>4</td>
<td>1036.3 sec</td>
<td>3710.8 sec</td>
</tr>
<tr>
<td>5</td>
<td>2117.9 sec</td>
<td>9261.3 sec</td>
</tr>
<tr>
<td>6</td>
<td>3.43 hours</td>
<td>24 - 26 hours</td>
</tr>
</tbody>
</table>

Table IV: Running Time Improvement

probability, it is not beneficial for the defender to protect other nodes except node 3 since it has the highest node value and attacking time.

In Figure 3b, we fixed $r_3$ through $r_5$ and increase $r_1$ and $r_2$ by adding a random noise uniformly distributed between $\text{noise level} - 1$, $\text{noise level} + 0.1$. We vary the noise level from 1 to 10. As shown in the figure, $m_1$ and $m_2$ keep increasing when the noise level becomes larger, while the defending frequencies for all other three nodes decrease due to limited defending resources, which indicates that the defender should protect the nodes with higher values more frequently in the subgame perfect equilibrium.

Table IV compares the running time of Algorithm 1 and that of the corresponding algorithm in our conference paper [36]. All experiments are conducted on a desktop with 4-Core Intel i5-4670K CPU @ 3.40GHz and Matlab R2019a. The same simulation setting as in Figure 3a is applied with fixed $M = 0.2$. We observe that Algorithm 1 is much faster than the original algorithm in our conference paper and the improvement is more significant in a larger setting.

VIII. CONCLUSION

In this paper, we propose a two-player non-zero-sum game for protecting a system of multiple components against a stealthy attacker where the defender’s behavior is fully observable and both players have strict resource constraints. We prove that periodic defense and non-adaptive i.i.d. attack are a pair of best-response strategies with respect to each other in the space of both adaptive and non-adaptive strategies. For this pair of strategies, we characterize the set of Nash Equilibria of the game, and show that there is always one (and maybe more) equilibrium, for the case when the attack times are deterministic. We further study the sequential game where the defender first publicly announces its strategy and design an algorithm that can identify a strategy that is arbitrarily close to the subgame perfect equilibrium strategy for the defender. We also provide a full analysis of the algorithm performance and its complexity guarantee.

REFERENCES

IX. APPENDIX

A. Proof of Lemma IV.4

Proof. In order to get the attacker’s best responses against any defender’s deterministic strategies, we can divide (6) into $N * L$ sub-optimization problems

$$\min_{W_{i,k}} E[\min(W_{i,k} + \alpha_{i,k}, X_{i,k})] - \max_{W_{i,k}} P(W_{i,k} < X_{i,k})C_i^A \leq M_{i,k}$$

where $\sum_{i=1}^{N} \sum_{k=1}^{L_i} M_{i,k} = M$ and $M_{i,k}$ can be arbitrary positive number. Note that we consider the equivalent minimization problem by taking the negative of the target function of (3) and omitting the constant part. We claim that, the optimal solution to (19) is to allocate as much budget as possible to $P(W_{i,k} = 0)$, that is

$$W_{i,k}^* = \begin{cases} 0 & \text{w.p. } p_{i,k}^0 \geq X_{i,k} \\ \text{w.p. } 1 - p_{i,k}^0 & \end{cases}$$

where $p_{i,k}^0 = \min(1, \frac{M_{i,k} T}{E[\min(\alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A})$ if $r_i(E[\min(\alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A) < 0$, and $p_{i,k}^0 = 0$ otherwise.

Since $M_{i,k}$ is any number such that $\sum_{i=1}^{N} \sum_{k=1}^{L_i} M_{i,k} = M$, the optimal solution of (6) also satisfies the same structure of (20). We then prove our claim. For simplicity, we assume that $W_{i,k}$ is a discrete r.v., and without loss of generality, it has the following p.m.f

$$W_{i,k} = \begin{cases} v_i & \text{w.p. } p_i, \ i = 1 \cdots n \\ \geq X_{i,k} & \text{w.p. } 1 - \sum_{j=0}^{n} p_j \end{cases}$$

where $n \in \mathbb{N}$ such that $0 < v_1 < v_2 < \ldots < v_n < X_{i,k}$. The following proof can be adapted to the continuous $W_{i,k}$ as well by replacing sums with integrals and p.m.f with p.d.f.

Putting (21) into (19), attacker’s problem can then be converted to the following form

$$\min_{j=0}^{n} p_j (r_i(E[\min(v_j + \alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A) + X_{i,k}r_i)$$

with two constraints: $\sum_{j=0}^{n} p_j E[\min(\alpha_{i,k}, X_{i,k} - v_j)] \leq M_{i,k}T$ and $\sum_{j=0}^{n} p_j \leq 1$, where $v_0 = 0$.

Let $J(\{p_0, \ldots, p_n\})$ denote the objective function in (22). Since $r_i(E[\min(\alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A < r_i(E[\min(v_j + \alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A)$, if $r_i(E[\min(\alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A) \geq 0$, $J(\{p_0, \ldots, p_n\})$ is minimized by setting $p_i = 0, \forall j = 0, \ldots, n$, which implies $W_{i,k} \geq X_{i,k}$ w.p.1. Such condition describes the case that even if the attacker attacks the node immediately after it is recovered, its reward is still less than 0. Therefore, the attacker never attacks. If $r_i(E[\min(\alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A < 0$, we claim that the optimal solution is to allocate as much budget $M_{i,k}T$ as possible to $p_0$, that is, we set all $p_j = 0, 1 \leq j \leq n$, and $p_0 = \min(1, \frac{M_{i,k} T}{E[\min(\alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A})$. This is clearly true if $r_i(E[\min(v_j + \alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A) \geq 0$. Therefore, it suffices to consider the case when $r_i(E[\min(\alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A < r_i(E[\min(v_j + \alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A).$

To prove the claim, consider an optimal solution $\{p_0, p_1, \ldots, p_n\}$ to (22). We show that if $p_0 < \min(1, E[\min(\alpha_{i,k}, X_{i,k})])$, then we can find another optimal solution $\{p'_0, p'_1, \ldots, p'_n\}$ such that $p'_0 > p_0$. We distinguish the following two cases:

Case 1: $p_0 E[\min(\alpha_{i,k}, X_{i,k})] + \sum_{j=1}^{n} p_j E[\min(\alpha_{i,k}, X_{i,k} - v_j)] < M_{i,k}T$. Then by the optimality of $\{p_0, p_1, \ldots, p_n\}$ and the assumption that $r_i(E[\min(v_j + \alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A < 0$, we must have $\sum_{j=0}^{n} p_j = 1$. Let $j \geq 1$ denote an index such that $p_j > 0$. Then there must exist a small amount $\Delta p > 0$ such that $p'_0 = p_0 + \Delta p, p'_j = p_j - \Delta p, p'_k = p_k, \forall k \neq j$ is again a feasible solution to (22). We further have

$$J(\{p_0, \ldots, p_n\}) - J(\{p'_0, \ldots, p'_n\})$$

$$= \Delta p (r_i(E[\min(v_j + \alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A)$$

$$- \Delta p (r_i(E[\min(\alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A)$$

$$= \Delta pr_i(E[\min(v_j + \alpha_{i,k}, X_{i,k})] - E[\min(\alpha_{i,k}, X_{i,k})])$$

$$\geq 0$$

Case 2: $p_0 E[\min(\alpha_{i,k}, X_{i,k})] + \sum_{j=1}^{n} p_j E[\min(\alpha_{i,k}, X_{i,k} - v_j)] > M_{i,k}T$. Again let $j \geq 1$ denote an index such that $p_j > 0$. Then there must exist a small amount $\Delta M > 0$ such that $p'_0 = p_0 + \frac{\Delta M}{E[\min(\alpha_{i,k}, X_{i,k})]} - p'_j = p_j - \frac{\Delta M}{E[\min(\alpha_{i,k}, X_{i,k} - v_j)]} p'_k = p_k, \forall k \neq j$ is a feasible solution to (22). We further have

$$J(\{p_0, \ldots, p_n\}) - J(\{p'_0, \ldots, p'_n\})$$

$$= \frac{\Delta M (r_i(E[\min(v_j + \alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A)}{E[\min(\alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A)$$

$$- \Delta M (r_i(E[\min(\alpha_{i,k}, X_{i,k})] - X_{i,k} + C_i^A)$$

$$= \frac{\Delta M}{E[\min(\alpha_{i,k}, X_{i,k})]} (r_i v_j - r_i X_{i,k} + C_i^A)$$

$$\geq 0$$

□

B. Proof of Theorem IV.3

Proof. When the attacker’s strategy is an ergodic Markov chain, the $p_{i,k}$’s time-average distribution is the same as its steady state distribution. Therefore the defender’s problem (1) can be transferred to the following

$$\max_{\{X_{i,k}\}, L_i} \lim_{T \to \infty} E \left[ \sum_{i=1}^{N} \left( \frac{L_i C_i^D + T r_i}{2} + \frac{1}{T} \sum_{k=1}^{L_i} E[p_{i,k}] \min(\alpha_{i,k}, X_{i,k}) + \left(1 - E[p_{i,k}]\right) X_{i,k} \cdot r_i \right) \right]$$

with the same resource constraint in (2) where the expectation in the numerator is with respect to the steady-state distribution of $p_{i,k}$. We find that (23) is the same as (1) if we set

$$W_{i,k}^* = \begin{cases} 0 & \text{w.p. } E[p_{i,k}] \\ \infty & \text{w.p. } 1 - E[p_{i,k}] \end{cases}$$

Here, $E[p_{i,k}]$ is the expected value of $p_{i,k}$’s steady state distribution. Therefore, based on Lemma IV.1 and Theo-
rem IV.1, we know that the periodic strategy is defender’s best response.

C. Proof of Lemma VI.3

Proof. Suppose the set allocation and \( \rho_d \) are fixed, which means \( m_i \) and \( \overline{m}_i \) \( \forall i \) are also fixed. According to Lemma VI.2, we can now convert (15)-(16) to the following problem:

\[
\max_{m_i, \alpha_d \in F} \sum_{i \in F} m_i (r_i \alpha_i - C^D_i) - r_i - \sum_{i \in G} r_i - \sum_{i \in E} m_i C^D_i + m_d (p_d \alpha_d - C^D_d) - p_d \tag{25}
\]

with constraints: \( \sum_{i \in F} m_i \leq B - \sum_{i \in E} \overline{m}_i - m_d \), \( \sum_{i \in F} \alpha_d m_i + p_d m_d \leq M \) and \( 0 \leq m_i \leq \overline{m}_i \) \( \forall i \in F \), where \( p = \min \{1, \frac{M - \sum_{i \in E} \alpha_d m_i}{\alpha_d m_d} \} \).

Case 1: If \( \frac{M - \sum_{i \in E} \alpha_d m_i}{\alpha_d m_d} \leq 1 \), we put \( p = \frac{M - \sum_{i \in E} \alpha_d m_i}{\alpha_d m_d} \) back into the target function of (25) and convert it to:

\[
\max_{m_i, \alpha_d \in F} \sum_{i \in F} m_i (r_i \alpha_i - C^D_i) - r_i - \sum_{i \in G} r_i - \sum_{i \in E} m_i C^D_i + \frac{M - \sum_{i \in E} \alpha_d m_i}{\alpha_d m_d} r_d (\alpha_d m_d - 1) - m_d C^D_d \tag{26}
\]

with constraints: \( \sum_{i \in F} m_i \leq B - \sum_{i \in E} \overline{m}_i - m_d \) and \( 0 \leq m_i \leq \overline{m}_i \) \( \forall i \in F \).

It is easy to see that (26) is a fractional knapsack problem. Thus, there is at most one fractional variable which means at most one \( m_i < \overline{m}_i \).

Case 2: If \( \frac{M - \sum_{i \in E} \alpha_d m_i}{\alpha_d m_d} > 1 \), the attacker’s budget is not fully utilized and all \( \rho^*_d \) in (15) equal to 1. Thus, the sets \( D \) and \( E \) are empty. Now suppose there exist two nodes \( j \) and \( k \) in \( F \) with \( m_j < \overline{m}_j \) and \( m_k < \overline{m}_k \). Without loss of generality, by assuming \( r_j \alpha_j - C^D_j \geq r_k \alpha_k - C^D_k \), we can always increase the defender’s payoff by decreasing \( m_k \) and increasing \( m_j \) until either \( m_j = \overline{m}_j \) or \( m_k = 0 \). If \( m_k = 0 \), node \( k \) is in set \( G \). Here, if the attacker’s budget is fully utilized (as in Case 1), we cannot guarantee the new payoff by decreasing \( m_k \) and increasing \( m_j \) is always bigger, since \( \alpha_k \) may be much smaller than \( \alpha_j \), making the increase of \( m_j \) is very small due to limited attacker’s budget.

Above all, we can claim that there exists an optimal solution with at most one node in set \( F \) with \( m_i < \overline{m}_i \). \( \square \)

D. Proof of Theorem VI.1

Proof. If the set \( G \) is empty in the optimal solution \( P^* \), Algorithm 1 computes the optimal payoffs for the defender by solving (17). Then, we have \( \max_{d, f} Val(d, f) = P^* \). Therefore, \( |P_{alg}| = 1 \).

If the set \( G \) is not empty in the optimal solution \( P^* \), we first consider the loss of performance due to \( \rho_{step} \). Denote \( \rho^*_d \) as the optimal \( \rho_d \) for computing \( P^* \) and \( \rho' \) the first \( \rho_d \) that is greater than \( \rho^* \) in Algorithm 1. Let \( m^*_i = m_i(\rho^*_d) \) and \( \overline{m}^*_i = m_i(\rho') \). Let \( |P_{\rho}^*| \) refer to the total cost when \( \rho^* \) increases to \( \rho' \) for the optimal solution \( P^* \). By increasing \( \rho^* \) to \( \rho' \), each \( \overline{m}^*_i \) decreases to \( m^*_i \) and the total cost increases in two parts. The first part is due to the decrease of \( \overline{m}_i \) for all \( i \) in \( F \). The second part comes from sets \( E \) and \( D \). Since \( \overline{m}_i \) decreases, the attacker has extra budget to attack the nodes in sets \( E \) and \( D \), moving these nodes to sets \( F \) and \( D \). For all

sets \( F, D, E \) and \( G \) above, we refer to the set allocation in optimal solution \( P^* \). Let \( H_F \) and \( H_E \) denote the increase of total cost from the two parts, respectively. We have

\[
H_F = \sum_{i \in F} \left[ r_i (1 - \overline{m}_i \alpha_i) + \overline{m}_i C^D_i - r_i (1 - m^*_i \alpha_i) - m^*_i C^D_i \right]
\]

\[
= \sum_{i \in F} \Delta \overline{m}_i (r_i \alpha_i - C^D_i)
\]

where \( \Delta \overline{m}_i = \overline{m}^*_i - \overline{m}_i \).

Let \( p'_d \) and \( p'_d \) be the attacker’s attacking probability for the node in set \( D \) under \( \rho' \) and \( \rho^* \), respectively. Denote \( p'_i \) as the attacking probability for node \( i \) under \( \rho' \). We have

\[
H_E = \sum_{i \in E} \left[ p'_i r_i (1 - m^*_i \alpha_i) + m^*_i C^D_i - m^*_i C^D_i \right]
\]

\[
= \sum_{i \in E} \Delta m^*_i (p'_i r_i - m^*_i C^D_i) + \sum_{i \in E} \Delta m^*_i (p'_i r_i - m^*_i C^D_i)
\]

\[
\leq \sum_{i \in E} p'_i r_i (1 - m^*_i \alpha_i)
\]

Also note that \( p'_i, i \in E \cup D \) must satisfy the resource constraint such that

\[
\sum_{i \in E \cup D} p'_i m^*_i \alpha_i \leq \sum_{i = 1}^{N} \Delta m^*_i \alpha_i
\]

where the right-hand side represents an upper bound on the extra budget for nodes in sets \( E \) and \( D \). From (27) and (28), we have

\[
HE \leq \sum_{i = 1}^{N} \Delta m^*_i \alpha_i \cdot \max_i \left\{ \frac{r_i (1 - \alpha_i \overline{m}_i)}{\alpha_i \overline{m}_i} \right\}
\]

We further have

\[
\Delta \overline{m}_i = \frac{(p^* + r_i) \alpha_i + C^A_i - (p' + r_i) \alpha_i + C^A_i}{\rho_{step} r_i} \leq \left[ \frac{(p^* + r_i) \alpha_i + C^A_i}{(p' + r_i) \alpha_i + C^A_i} \right] \tag{29}
\]

Since \( \rho' \) is one of the \( \rho_d \) that Algorithm 1 iterates through, we have \( |P_{alg}| \leq |P_{\rho'}| \). Then, we can compute the approximation ratio as follows:

\[
\frac{|P_{alg}| - |P^*|}{|P^*|} \leq \frac{|P_{\rho'}| - |P^*|}{|P^*|} = HE + HE \leq \sum_{i \in F \cup D} \Delta m^*_i (r_i \alpha_i - C^D_i) |P^*| \leq \sum_{i \in F \cup D} \Delta m^*_i (r_i \alpha_i - C^D_i) \left( \sum_{i = 1}^{N} \Delta m^*_i \alpha_i \cdot \max_i \left\{ \frac{r_i (1 - \alpha_i \overline{m}_i)}{\alpha_i \overline{m}_i} \right\} \right)
\]

\[
\leq \rho_{step} \left( \max_i \left\{ \frac{\alpha_i}{C^A_i} \right\} + N \cdot \frac{\max_i \left\{ \frac{\alpha_i}{C^A_i} \right\} \left( 1 + \max_i \left\{ \frac{\alpha_i}{C^A_i} \right\} \right) m_i \overline{m}_i \alpha_i \right) \min_i r_i \leq \rho_{step} \cdot O(N) \tag{30}
\]

A similar argument can be used to bound the loss of performance due to rounding parameter \( \delta \). The only difference is the decrease of \( m^*_i \) which satisfies \( \Delta m^*_i \leq \frac{\rho_{step} r_i (\alpha_i + C^A_i)^2}{(p^* + r_i) \alpha_i + C^A_i} + \delta \).

The rest is very similar to (30). It follows that \( \frac{|P_{alg}|}{|P^*|} \leq 1 + \delta \cdot O(N) \) as desired. \( \square \)