Dynamic Connectivity Game for Adversarial Internet of Battlefield Things Systems

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Abstract—In this paper, the problem of network connectivity is studied for an adversarial Internet of Battlefield Things (IoBT) system in which an attacker aims at disrupting the connectivity of the network by choosing to compromise one of the IoBT nodes at each time epoch. To counter such attacks, an IoBT defender attempts to reestablish the IoBT connectivity by either deploying new IoBT nodes or by changing the roles of existing nodes. This problem is formulated as a dynamic multistage Stackelberg connectivity game that extends classical connectivity games and that explicitly takes into account the characteristics and requirements of the IoBT network. In particular, the defender’s payoff captures the IoBT latency as well as the sum of weights of disconnected nodes at each stage of the game. Due to the dependence of the attacker’s and defender’s actions at each stage of the game on the network state, the feedback Stackelberg solution (FSE) is used to solve the IoBT connectivity game. Then, sufficient conditions under which the IoBT system will remain connected, when the FSE solution is used, are determined analytically. Numerical results show that the expected number of disconnected sensors, when the FSE solution is used, decreases up to 62% compared to a baseline scenario in which a Stackelberg game with no feedback is used, and up to 57% compared to a baseline equal probability policy.

I. INTRODUCTION

THE Internet of Things (IoT) is expected to revolutionize the military battlefield in various aspects [1]–[3]. By interconnecting all military units, including soldiers and vehicles, with various IoT devices, sensors, and actuators, the IoT provides autonomy in the battlefield and increases the efficiency of military networks. An IoT-enabled battlefield will allow military commanders to acquire instantaneous information on the status of the military units. For instance, wearables can provide instant updates on the situation of soldiers, and sensors mounted on vehicles can provide real-time information on the status of each vehicle. Another important feature of IoT that makes it suitable for the battlefield is that it supports mobile crowdsensing. In mobile crowdsensing, various IoT devices such as handheld devices, wearables, vehicles, and sensors collaborate in sensing a particular type of information. In traditional military networks, on the other hand, dedicated sensors are deployed for each application. Thus, a dense deployment of IoT devices can provide more accurate and detailed information about the battlefield, which can, in turn, allow building comprehensive situation awareness and enabling more accurate decision making. This imminent integration of IoT with military networks forms the nexus of the so-called Internet of Battlefield Things (IoBT) [1].

Naturally, in an IoBT, connectivity is very critical for the successful operation of the military network as it is essential to maintain the autonomy of the system. Military missions, such as surveillance and situational awareness, will heavily rely on the information collected for the battlefield, and thus, any disconnection in the IoBT system will result in inaccurate decision making and poor situational awareness. In fact, the IoBT is more vulnerable than commercial IoT networks due to the adversarial nature of the battlefield, in which the devices are subject to security attacks. Moreover, IoT devices are typically small and low-cost devices that do not support strong security mechanisms, and hence, they can be easily compromised by adversaries. The vulnerability of the IoBT devices necessitates the design of novel security solutions that are robust to adversaries and that can maintain the connectivity of the IoBT in adversarial settings.

Connectivity reconstruction solutions were initially designed for wireless networks such as in [4] in which the nodes select their transmission powers to maintain network connectivity. In [5] and [6], connectivity establishment mechanisms are proposed to reestablish connectivity between sensors that were isolated, due to faults or attacks, and a central sink in a sensor network. In [5], the connectivity problem is formulated as a single leader, multiple followers Stackelberg game in which a cloud acts as the leader and chooses to activate sleep nodes in order to maintain full connectivity, whereas the sleep nodes act as followers with each seeking to maximize the number of isolated nodes that it reconnects to the network. In [6], stochastic geometry is used to design a relay-based connectivity recovery scheme for a wireless sensor network whose goal is to optimize the tradeoff between the number of selected relays and the energy spent to restore connectivity. In [7], the authors derive conditions for regional connectivity in an IoT industrial system while optimizing sensor coverage. In [8], a dynamic clustering and routing algorithm is proposed to maintain connectivity and achieve energy efficiency in a large scale sensor network. In [9], a dynamic mobile-aware IoT topology control scheme, based on a potential game, is proposed in order to optimize IoT connectivity. The work in [10] proposes a resilience mechanism to maintain percolation-based connectivity in an IoT network in which an adversary seeks to attack highly connected IoT nodes in order to achieve the maximum possible damage. In the model of [10], the IoT nodes report a one bit estimate of their attack status to a common fusion center. Then, the objective of the fusion center is to choose the nodes to survey such that the number of nodes with highest degree under attack is kept below a
required threshold. The problem is formulated as a zero sum game between the fusion center and the attacker. In [11], a time-reversal scheme is proposed in an IoT network to enable connectivity between devices with heterogeneous bandwidth requirements.

However, most of these existing works [4]–[11] consider the connectivity problem in conventional sensor networks in which all the nodes are simple sensors of the same type and capabilities, whereas in the IoBT, the nodes can have heterogeneous roles and capabilities. In fact, each IoBT device can possess multiple sensors each of which is collecting different types of information. Thus, the importance of each device is dependent on the number of types of information it is sensing. Further, the IoBT will integrate high end nodes, commonly known as sinks, that collect the different information from the IoBT devices and perform complex operations in order to obtain useful information needed by the military commanders [1]–[3]. Thus, the effect of disconnection on the IoBT depends on the type of the node that gets isolated from the network. Further, prior art such as in [4]–[11] does not adequately capture the dynamics of interaction between defenders and adversaries in a battlefield. Thus, there is a need to introduce new dynamic connectivity solutions that consider the heterogeneity of the IoBT nodes and dynamically adapt to the actions of adversaries in the battlefield.

The main contributions of this paper are summarized next:

- We develop a novel adaptive framework for dynamically optimizing the connectivity of an adversarial IoBT network. In particular, we consider the connectivity problem in an IoBT that includes a set of heterogeneous devices that sense different types of information. The IoBT devices must transmit their information, through intermediary local sinks, to the general sink. We consider an adversarial IoBT in which an attacker is interested in causing disconnection to the network by choosing to compromise one of the IoBT nodes at each time epoch. Meanwhile, the IoBT operator acts as a defender that strives to maintain the connectivity of the IoBT network by either deploying new IoBT nodes or changing the roles of the nodes. The objective of the attacker and the defender is to maximize their sum of payoffs until the end of the military operation.

- We formulate the connectivity problem in the IoBT using the framework of connectivity games [12] which are game-theoretic frameworks suitable for addressing problems that involve the maintenance and restoration of a network in presence of adversaries. However, in classical connectivity games, the sole objective is to restore or maintain the network connectivity, whereas in the IoBT, there are other performance metrics that must be considered such as the latency of communication. Thus, we propose a novel IoBT connectivity game that is tailored to the characteristics and requirements of the IoBT. In particular, the attacker’s payoff is expressed as the sum of weights of disconnected nodes minus the cost of compromising a node. The defender’s payoff, on the other hand, is expressed as the utility of deploying a new node minus the sum of weights of disconnected nodes, the time required to deliver the information to the IoBT general sink, and the cost of deploying a new node. Further, in the studied IoBT connectivity problem, the defender must maintain the number of IoBT devices sensing the same type of information above a certain required threshold. Thus, the defender’s strategy set is coupled with the attacker’s action at each time epoch. Consequently, we cast the problem as a dynamic multistage Stackelberg connectivity game in which, at each stage of the game, the attacker acts as a leader, and the defender acts as a follower. Due to the dependence of the attacker’s and defender’s actions in each stage of the game on the network state, the feedback Stackelberg equilibrium (FSE) is used to solve the IoBT connectivity game.

- We analytically derive sufficient conditions for the IoBT network to remain connected at each stage of the game when the FSE solution is used. Numerical results show that the expected number of disconnected sensors, when the FSE solution is used, decreases up to 62% compared to a baseline scenario in which a Stackelberg game with no feedback is used, and up to 57% compared to a baseline equal probability policy.

The paper is organized as follows: Section I describes the adversarial IoT system model. Section II presents the formulation of the IoBT connectivity game. Section III presents the feedback Stackelberg solution of the IoBT game. Section IV presents sufficient connectivity conditions of the IoBT network when the FSE is used. Section V presents the simulations results and analysis. Finally, conclusions are drawn in Section VI.

II. SYSTEM MODEL

Consider an IoBT network composed of a set $D$ of heterogeneous devices that can be of different types within a set $K$ of size $K$. Each IoBT device can possibly represent a vehicle, a drone, a robot, a surveillance camera, a sensor dedicated for a certain type of application, a sensor-actuator pair or a soldier equipped with wearable sensors. Each device of type $\tau \in K$ encompasses $N_{\tau}$ sensors (and their corresponding actuators) sensing a subset $H_{\tau}$ of a set $I$ of types of information. Due to the heterogeneity of the IoBT nodes, in terms of roles and capabilities, we consider a hierarchical tree structure [14]. The hierarchical IoBT structure provides scalability and allows the system operator to easily add new devices, which is suitable for a large-scale IoBT system. The area that the IoBT network spans is divided into subareas $A_1, A_2, \ldots, A_H$. Within each area $A_h$, devices sensing the same type of information $j \in I$ are organized into a cluster $D_{jh}$. Thus, an IoBT device equipped with multiple sensors can belong to several clusters. Within each cluster, one of the devices is chosen to be a cluster head (CH), and, thus, the rest of the devices transmit their sensed data to the CH. The CH then collects the information received from the devices in the cluster and sends it to a local sink (LS) serving subarea $A_h$.

In each subarea $A_h$, multiple LSs can be deployed for redundancy. At any time epoch $t$, only one LS is activated in each subarea $A_h$. Deploying redundant LSs ensures that there is a substitute for the activated LS in case of failure.
or malfunction. At each time epoch $t$, each activated LS processes its information and performs more sophisticated operations such as augmented sensing and extraction of useful information as requested by the general sink (GS). The GS is a high end node that eventually processes the information received from the activated LSs in order to identify events requested by the military commanders and provide situational awareness. Since the nodes in the considered IoBT are of heterogeneous capabilities and roles, each node $i$ is assigned a weight $w_i$ depending on its importance. The weight $w_i$ of each device $i \in D$ of type $\tau$ is measured in terms of the number of different sensors that the device includes i.e. $w_i = N_x$. LSs, on the other hand, perform more sophisticated operations. Thus, each LS $l$ is assigned weight $w_{L,l}$ higher than the weights of the devices i.e. $w_{L,l} > \max_{1 \leq x \leq K} N_x$.

In this IoBT, an attacker is interested in minimizing the connectivity of the network to prevent the GS from detecting important events thus ultimately impairing its decisions. To achieve this goal, the attacker chooses at each time $t$ to compromise one of the nodes in $B = \cup_{h=1}^{H} L_h \cup D$ where $L_h$ is the set of LSs in subarea $A_h$. In fact, the attacker chooses the node which maximizes its payoff which is expressed as the sum of weights of all nodes that will be disconnected from the GS, and the cost of compromising node $i$ at each time $t$. This cost pertains to the resources needed to compromise the targeted node. Let $c_r$ be the cost of compromising device of type $\tau$ and $c_L$ be the cost of compromising an LS. The attacker also incurs additional costs $c_{CH}$ and $c_{aL}$ in order to determine the CH of each cluster or the activated LS in each subarea. The costs $c_{CH}$ and $c_{aL}$ can represent, for example, the security costs of intercepting the beacon messages of the CH or the activated LS to the remaining devices. Thus, the total cost of attacking device $i$ of type $\tau$ in subarea $A_h$ is given by: $c_i = c_r + \sum_{j=1}^{M} x_{ijh} c_{CH}$ where $x_{ijh} = 1$ indicates that device $i$ is the CH of cluster $D_{jh}$ or $x_{ijh} = 0$, otherwise. The total cost incurred by attacking LS $l$ in subarea $A_h$ is given by: $c_{L,l} = c_{LS} + y_{lh} c_{aL}$ where $y_{lh}$ is the indicator that LS $l$ is activated in subarea $A_h$. In order to thwart the attacks made at each time epoch $t$, the defender can choose one of the following actions:

1) Deploys a new device of type $\tau$ in subarea $A_h$;
2) Changes the cluster head in cluster $D_{jh}$;
3) Changes the activated LS in subarea $A_h$;
4) Deploys a new LS in area $A_h$.

Action 1) helps in maintaining the necessary amount of sensors to maximize the amount of useful information gathered within an area. Actions 2) and 3) ensure the robustness of the network in case the current activated LS or CH fails or is destroyed by the attacker. In practice, the newly deployed devices are brought from a warehouse that is in the proximity of the battlefield. Action 4) ensures that there will always exist an LS that could serve the sensors in any subarea in case the activated LS fails or is compromised by the attacker. For actions 1) and 4), the defender will incur a cost of deploying a device or an LS. Let $d_L$ be the cost of deploying a device of type $\tau$ and let $d_L$ be the cost of deploying an LS. In an IoBT, the newly deployed devices and LSs are initially stored, prior to deployment, in a storage facility (or a military base) that is in the proximity of the IoBT network and is assumed to be secured from the attacker.

The objective of the defender is to maximize a payoff that captures the difference between the achieved utility and the sum of its costs until the end of the military operation at time epoch $T$ subject to the constraint that the number of sensors $N_{jh}(t)$ sensing information of type $j$ in subarea $A_h$ at each time epoch $t$ does not fall below a certain threshold $N_{th,jh}$. This constraint ensures that the GS as well as the LSs obtain the necessary information of type $j$ in a certain subarea $A_h$. The utility achieved from deploying a device of type $\tau$ in subarea $A_h$ is expressed in terms of the number of clusters that will restore their number of sensors above the threshold and is given by $u_{\tau} = \sum_{j=1}^{M} I_j(t) = \sum_{j=1}^{M} I_j(t)$ where $I_j(t)$ is an indicator function. The utility achieved from deploying an LS in subarea $A_h$ is given by $u_L = B - L_h$ where $L_h = |L_h|$ and $B$ is a constant that reflects the recommended number of LSs in each subarea. The defender’s utility is the utility of deploying a new device or an LS. The defender’s cost at each time epoch $t$ is expressed in terms of the sum of weights of disconnected nodes, the time spent to deliver the information to the GS, and the cost of deploying a new node.

Due to the clear dependence between the goals and the actions of the attacker and the defender as well as the impact of the attacker and defender’s actions on the IoBT network graph, the problem will be formulated as a noncooperative positional game [12] and [13], as explained next.

### III. IoBT Connectivity Game

Connectivity games are game-theoretic models [12] that capture situations which require the maintainance and restoration of the normal operations of a given network. Connectivity games typically involve two players: a constructor who is responsible for restoration of nodes as well as the addition of new nodes, and a destructor who deletes nodes from the network. The constructor in our game is the IoBT defender whereas the destructor is the attacker. A connectivity game [12] is an interactive game in which the constructor and the destructor play in alternation until one of the players wins the game. The winning condition for the constructor involves maintaining the connectivity of the network. In particular, there are two types of objective considered in classical connectivity games [12]: 1) a safety objective in which the
constructor must maintain the connectivity of the network in every step of the game and 2) a reachability objective in which the constructor must obtain a connected network starting from a disconnected network.

However, in the IoBT setting, the objective is not only to maintain the network connectivity but also to maximize the network efficiency (for example in terms of energy efficiency and latency). Further, in the IoBT setting, devices sense different types of information, and in order to obtain the necessary information of each type in a certain area, there is a need to ensure that the number of devices sensing the same type of information does not drop below a required threshold. Moreover, in a real-world IoBT, there is a cost incurred when a device is destroyed by the attacker or deployed by the defender, which is not considered in a classical connectivity game [12]. The heterogeneity of the IoBT devices, in terms of their importance and roles, is also not taken into account in classical connectivity games [12].

Given these requirements and characteristics of the IoBT network, we consider an IoBT connectivity game that extends classical connectivity games. The IoBT connectivity game is formulated as a discrete-time deterministic game \((P, \mathcal{T}, \mathcal{X}, (S_{a,t}, S_{d,t})) \in \mathcal{E})\) with a finite number of stages, where the set of players \(P\) are the attacker and the defender, and the set of stages \(\mathcal{T} = \{1, 2, ..., T\}\). In this IoBT connectivity game, the defender must observe the attacker action before choosing its optimal action in order to maintain the number of devices in each area above the required threshold. Thus, the IoBT connectivity game is formulated as a Stackelberg game in which, at each stage \(t\) of the game, the attacker acts as the leader, and the defender acts as the follower. The state space \(\mathcal{X} = \mathcal{X}_a \times \mathcal{X}_d\) is the set of all observed IoBT networks by the attacker and the defender up to stage \(T\). The state of the game at stage \(t\) is \(\psi_t = (\psi_{a,t}, \psi_{d,t}) \in \mathcal{X}\) where \(\psi_{a,t}\) is the network observed by the attacker and \(\psi_{d,t}\) is the network observed by the defender. The network state \(\psi_{a,t}\) observed by the attacker is given by:

\[
\psi_{a,t} = (D_a(t), \{L_a(h), 1 \leq h \leq H; \{D_{a,jh}(t), 1 \leq j \leq I, 1 \leq h \leq H; \{f_{a,jh}(t), 1 \leq j \leq I, 1 \leq h \leq H; \})\} \text{ where } D_a(t) \text{ represent the set of devices, } L_a(h) \text{ the set of LS in subarea } A_h, \text{ and } f_{a,jh}(t) \text{ is the index of the device that is the CH of } D_{a,jh}(t), \text{ and } s_{a,h}(t) \text{ is the index of the activated LS in subarea } A_h. \]

Similarly, the network state \(\psi_{d,t}\) observed by the defender is given by:

\[
\psi_{d,t} = (D_d(t), \{L_d(h), 1 \leq h \leq H; \{D_{d,jh}(t), 1 \leq j \leq I, 1 \leq h \leq H; \{f_{d,jh}(t), 1 \leq j \leq I, 1 \leq h \leq H; \})\} \text{ where } D_d(t) \text{ represent the set of devices, } L_d(h) \text{ the set of LS in subarea } A_h, \text{ and } f_{d,jh}(t) \text{ is the index of the device that is the CH of } D_{d,jh}(t), \text{ and } s_{d,h}(t) \text{ is the index of the activated LS in subarea } A_h. \]

In our game, the set of pure strategies of the attacker \(S_{a,t}(\psi_t)\) at stage \(t\) is \(S_{a,t}(\psi_t) = \{a_{d,i}, i \in D_a(t)\} \cup \{a_{L,h}, l \leq h \leq H\}, \) where action \(a_{d,i}\) corresponds to destroying device \(i\), and action \(a_{L,h}\) corresponds to destroying LS \(l\) in subarea \(A_h\). Due to the constraint on the number of devices in each cluster, the strategy set of the defender at each stage \(t\) is coupled to the attacker’s action \(a_t\) and is a function of the network state \(\psi_t\). Hence, the strategy set \(S_{d}(\psi_t, a_t)\) of the defender is

\[
S_{d}(\psi_t, a_t) = \left\{ \begin{array}{ll}
\{b_{d,rh}, \forall r \mid j \in H, \forall j \in Y_{i,h}(t)\} & \text{if } C_1(a_t), \\
\{\mathcal{Q}_d, \} & \text{otherwise},
\end{array} \right.
\]

where condition \(C_1(a_t) = a_t = a_{d,i}, \exists j \text{ s.t. } i \in D_{a,jh}(t), N_{a,jh}(t) \leq N_{a,jh}, \) the set \(Y_{i,h}(t) = \{j \in \mathcal{I} \mid i \in D_{a,jh}(t), N_{d,jh}(t) < N_{a,jh}\}, \) \(N_{d,jh}(t)\) is the number of devices in cluster \(D_{d,jh}(t)\) in network \(\psi_{d,t}\), \(N_{a,jh}(t)\) is the number of devices in cluster \(D_{a,jh}(t)\) in network \(\psi_{a,t}\), and the set \(\mathcal{Q}_d\) is the set of all possible strategies of the defender given by

\[
\mathcal{Q}_d = \{b_{c,ijh}, i \in D_{a,jh}(t), 1 \leq j \leq M, 1 \leq h \leq H\} \\
\cup \{b_{d,rh}, 1 \leq \tau \leq K, 1 \leq h \leq H\} \\
\cup \{b_{L,h}, 1 \leq h \leq H\}. \]

Action \(b_{d,rh}\) corresponds to deploying a new device of type \(\tau\) in subarea \(A_h\), action \(b_{c,ijh}\) corresponds to assigning device \(i\) to be the CH of cluster \(D_{a,jh}(t)\), action \(b_{L,h}\) corresponds to deploying a new LS in subarea \(A_h\), and action \(b_{c,ijh}\) corresponds to activating LS \(l\) in subarea \(A_h\). According to [12], if the attacker destroys a device and causes the number of the devices in some clusters to drop below the required threshold, the strategy set of the defender will only include the actions of deploying a device that restores the number of devices in each affected cluster to the required threshold.

Otherwise, the defender can choose either to change the CHs, change the LSs, deploy a new device, or deploy a new LS. The evolution of the attacker’s state \(\psi_{a,t}\) is given by

\[
D_a(t + 1) = \left\{ \begin{array}{ll}
D_a(t) \setminus \{i\} & \text{if } a_t = a_{d,i}, b_t \neq b_{d,rh}, \\
D_a(t) & \text{otherwise},
\end{array} \right.
\]

\[
L_a(h,t + 1) = \left\{ \begin{array}{ll}
L_a(h,t) \setminus \{i\} & \text{if } a_t = a_{L,h}, b_t \neq b_{L,h}, \\
L_a(h,t) & \text{otherwise},
\end{array} \right.
\]

\[
D_{a,jh}(t + 1) = \left\{ \begin{array}{ll}
D_{a,jh}(t) \setminus \{i\} & \text{if } a_t = a_{d,i}, i \in D_{a,jh}(t), b_t \neq b_{d,rh}, \\
D_{a,jh}(t) & \text{otherwise},
\end{array} \right.
\]

\[
f_{a,jh}(t + 1) = \left\{ \begin{array}{ll}
0 & \text{if } a_t = a_{d,i}, i \in D_{a,jh}(t), f_{a,jh}(t) = i, b_t \neq b_{c,ijh}, \\
f_{a,jh}(t) & \text{otherwise},
\end{array} \right.
\]

\[
f_{a,jh}(t) \text{, otherwise},
\]
\[ s_{a,t}(t+1) = \begin{cases} 0 & \text{if } a_t = a_{L,t}\,, \quad s_{a,b}(t) = l, \quad b_t \neq b_{a,t}\,, \\ l & \text{if } b_t = b_{a,t}\,, \quad a_t \in S_a(\psi_t), \\ s_{a,b}(t), \quad \text{otherwise, not.} \end{cases} \]

Similarly, the evolution of the defender’s state \( \psi_{d,t} \) is given by

\[ D_{d}(t+1) = \begin{cases} D_{d}(t) \setminus \{i\} & \text{if } a_{t+1} = a_{d,i}, \quad b_t \neq b_{d,t}\,, \\ D_{d}(t), \quad \text{otherwise.} \end{cases} \]

The attacker’s payoff at each stage \( t \) is expressed in terms of its utility which is the sum \( S_{D,t}(a_t, b_t, \psi_t) \) of weights of all nodes that will be disconnected from the GS, and the cost \( C_{a,t}(a_t, b_t) \) of destroying node \( i \), as follows:

\[ P_{a,t}(a_t, b_t, \psi_t) = S_{D,t}(a_t, b_t, \psi_t) - \nu C_{a,t}(a_t, b_t, \psi_t), \quad (13) \]

where \( \nu \) is a normalizing constant. The defender’s payoff at stage \( t \) is expressed in terms of its utility minus its cost as follows:

\[ P_{d,t}(a_t, b_t, \psi_t) = \eta S_{D,t}(a_t, b_t, \psi_t) - \mu \Lambda_{t}(a_t, b_t, \psi_t) - \lambda C_{d,t}(a_t, b_t, \psi_t), \quad (14) \]

where \( \eta, \mu, \) and \( \lambda \) are normalizing constants. For readability, the expressions of \( S_{D,t}(a_t, b_t), \Lambda_{t}(a_t, b_t, \psi_t), C_{a,t}(a_t, b_t, \psi_t), C_{d,t}(a_t, b_t, \psi_t) \) and \( U_{d,t}(a_t, b_t, \psi_t) \) in terms of each pair of the attacker’s and defender’s pure strategies \( a_t \) and \( b_t \) are given in the Appendix.

To increase the uncertainty of its action and improve its payoff, the attacker will use a mixed strategy \( q_t \) at each stage \( t \), thus randomizing its choices across its pure strategies. The defender, on the other hand, responds with a pure strategy \( b_t \) [16]. It is assumed that the defender can perfectly know the strategy of the attacker at each stage \( t \). The objective of the attacker is then to find the optimal mixed strategies \( q_1, q_2, ..., q_T \) that maximize the sum of its expected payoffs until stage \( T \)

\[ \max_{q_1, q_2, ..., q_T} \sum_{t=1}^{T} \sum_{a_t \in S_{a,t}} q_{a_t} P_{a,t}(a_t, b_t, \psi_t) \text{ s.t. } 1 \cdot q_t = 1 \quad \forall t, \quad (15) \]

where \( q_{a_t} \) is the probability with which the attacker chooses action \( a_t \) by the attacker. Similarly, the objective of the defender is to find the optimal strategies \( b_1, b_2, ..., b_T \) that maximizes the sum of its expected payoffs up to stage \( T \) i.e.

\[ \max_{b_1, b_2, ..., b_T} \sum_{t=1}^{T} \sum_{a_t \in S_{a,t}} q_{a_t} P_{d,t}(a_t, b_t, \psi_t) \text{ s.t. } b_t \in S_{d,t}(\psi_t, a_t) \quad \forall t. \quad (16) \]

Since the attacker’s and the defender’s actions are coupled to the current stage \( t \) and the state \( \psi_t \), the feedback Stackelberg equilibrium (FSE) will be used as a solution, as discussed next.

IV. FEEDBACK STACKELBERG SOLUTION

The FSE applies for situations in which the leader first chooses its strategy at time instant \( t \). Then, the follower chooses its strategy based on the current state and the leader’s action. In the proposed IoT connectivity game, the strategy sets \( S_{a,t}(\psi_t) \) and \( S_{d,t}(\psi_t, a_t) \) of both the attacker and the defender depend on the current state \( \psi_t \). Further, the defender strategy set \( S_{d,t}(\psi_t, a_t) \) at time instant \( t \) is dependent only on the attacker’s action \( a_t \) at the current time instant \( t \) according to [17]. Thus, the FSE is a suitable solution for our IoT connectivity game as opposed to the open-loop Stackelberg equilibrium solution where the leader determines its optimal actions for all stages simultaneously, and, then, the follower determines its optimal actions for all stages \( t = 1, 2, ..., T \). The FSE is subgame perfect and time consistent. Thus, at each stage \( t \) of the game, the FSE considers the immediate payoff at stage \( t \) as well as the expected sum of payoffs of the subsequent stages up to \( T \), in contrast to static Stackelberg games which only consider the immediate payoff at stage \( t \). Hence, the FSE solution obtained recursively using dynamic programming and solving a Stackelberg game at each stage \( t \) of the game. Further, the dynamic nature of the FSE solution makes it adaptive to system changes at any instant \( t \). In [17], it is shown that the FSE remains stable under stochastic Markovian perturbations of the system. The robustness and adaptability of the FSE solution is desirable for a dynamic IoT system that is constantly subject to random changes due to adversarial conditions.

Let \( q = (q_1, q_2, ..., q_T) \) and \( b = (b_1, b_2, ..., b_T) \) be respectively the strategy vectors of the attacker and the defender respectively. The FSE strategy will be

**Definition 1.** The strategy profile \((q^*, b^*)\) constitute a feedback Stackelberg equilibrium if \( \forall \psi_t \in X, t \in T \),

\[ \Omega_{a,t}(q_t^*, b_t^*, \psi_t) = \max_{q_t \in \mathcal{M}_{a,t}} \max_{b_t \in \mathcal{R}^d(q_t)} \Omega_{a,t}(q_t, b_t, \psi_t), \quad (17) \]

where \( \mathcal{M}_{a,t} \) is the space of mixed strategies of the attacker at stage \( t \), \( \Omega_{a,t}(q_t, b_t, \psi_t) \) is the expected payoff of the attacker starting from stage \( t \) and for a state \( \psi_t \), and \( \mathcal{R}^d(q_t) \) is the optimal strategy set of the defender to the mixed strategy \( q_t \) of the attacker and is given by
We define \( S'_{a,t}(b',\psi_t) \) as its mixed strategy of the attacker at stage \( t \), i.e.,
\[
S'_{a,t}(b',\psi_t) = \left\{ S_{a,t} \setminus R_{a,t} : \text{if } J_{a,t} \neq \phi, b'_t \in V_t, \right. \\
S_{a,t} \setminus R_{a,t} : \text{otherwise},
\]
where \( R_{a,t} = \{ a_{t,j,h} : s.t. i \in D_{j,h}(t), (j,h) \in J_{a,t}, \right. \\
V_t = Q_d \{ b'_{a_i,j,h} : s.t. j \in D_{j,h}(t), V_t \}, \text{the set } J_{a,t} = \{ j \in T \mid i \in D_{j,h}(t), N_{j,h}(t) < N_{a_i,j,h} \}, \text{and the set } Q_d \text{ is defined in (22).}
\]
Thus, at each stage \( t \), the attacker solves the following linear program for each strategy \( b'_t \) of the defender and given a network state \( \psi_t \) and for a given state \( \psi_t \), it determines the optimal probabilities of actions according to (23) while taking into account the best response of the defender defined in (21).

The proposed linear program holds under the assumption that the attacker has full knowledge of the defender's actions and payoffs at each time epoch \( \psi_t \). The conditions under which the IoT network remains connected are derived in the following section.

V. CONNECTIVITY CONDITIONS

In the IoT, maintaining connectivity at any time is critical for the successful operation of the network. Thus, the safety objective of connectivity games is more suitable to the IoT than the reachability objective. In our game, the connectivity of the IoT network is maintained at each stage \( t \) if the attacker does not choose an action that causes disconnection. Disconnection occurs if neither a cluster nor an entire subarea gets disconnected from the GS. To determine the connectivity conditions under which the IoT network remains connected, when the FSE solution is used, we first determine, for each action \( b'_t \) of the defender, the set \( Z_D(b'_t) \) of attacker's actions that cause disconnection:

\[
Z_D(b'_t) = S'_{a,t}(b'_t,\psi_t) \cap \left\{ V_1, \text{ if } b'_t = b_{a_i,j,h}, \right. \\
V_2, \text{ if } b'_t = b_d+r, \\
V_3, \text{ if } b'_t = b_{d,j,h}, \\
V_4, \text{ if } b'_t = b_{L,h}, \\
V_5, \text{ if } b'_t = b_{L,h}.
\]

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V_3, \text{ if } b'_t = b_{d,j,h}, \\
V_4, \text{ if } b'_t = b_{L,h}. \\
\]

Thus, given that the optimal action of the defender is \( b'_t \), disconnection does not occur if the attacker does not choose an action from the set \( Z_D(b'_t) \). Let
\[
F_{a,t}(a_t, b_t) = \min b_{a_t,j,h} \in Z_D(b'_t) \{ a_{t,j,h} \}
\]
and
\[
F_{a,t}(a_t, b_t) = \max b_{a_t,j,h} \in Z_D(b'_t) \{ a_{t,j,h} \}
\]
The following proposition provides sufficient conditions for the IoT network to remain connected when the FSE solution is used.

Proposition 1. The proposed FSE solution \( (q^*, b^*) \) maintains connectivity of the IoT network if for every \( \psi_t \in X_t \), \( t \in T \) for each \( a_t^* \in Z_D(b'_t) \), there exists \( a_t^* \in S'_{a,t}(b'_t,\psi_t) \) in \( Z_D(b'_t) \) in which one of the following conditions hold:

1. \( B_{a,t}(b'_t) = \phi \).

2. \( B_{a,t}(b'_t) \cup B_{a,t}(b'_t) \neq \phi, W \cdot F_{a,t}(a_t^*, b_t) > F_{a,t}(a_t^*, b_t) \).

3. \( B_{a,t}(b'_t) \neq \phi, B_{a,t}(b'_t) \neq \phi, \text{ and } \min b_{a_t,j,h} \in B_{a,t}(b'_t) \{ a_{t,j,h} \} \leq \min b_{a_t,j,h} \in B_{a,t}(b'_t) \{ a_{t,j,h} \} \).

4. \( B_{a,t}(b'_t) \neq \phi, B_{a,t}(b'_t) \neq \phi, \text{ and } \min b_{a_t,j,h} \in B_{a,t}(b'_t) \{ a_{t,j,h} \} \geq \min b_{a_t,j,h} \in B_{a,t}(b'_t) \{ a_{t,j,h} \} \).

5. \( B_{a,t}(b'_t) \cup B_{a,t}(b'_t) = \phi, F_{a,t}(a_t^*, b_t) > 0 \).
where \( B_{1,t}(b_t^i) = \{ b_t \in S_{dt,t} \mid F_{d,t}(a_{t}^i, b_t) - F_{d,t}(a_{t}^n, b_t^i) \geq 0, F_{d,t}(a_{t}^i, b_t) - F_{d,t}(a_{t}^n, b_t^i) \geq 0 \} \),
\( B_{2,t}(a_t^i) = \{ b_t \in S_{dt,t} \mid F_{d,t}(a_t^i, b_t) - F_{d,t}(a_t^n, b_t) < 0, F_{d,t}(a_t^i, b_t) - F_{d,t}(a_t^n, b_t^i) \leq 0 \} \),
\( B_{3,t}(b_t^i) = \{ b_t \in S_{dt,t} \mid F_{d,t}(a_t^i, b_t) - F_{d,t}(a_t^n, b_t^i) \geq 0, F_{d,t}(a_t^i, b_t) - F_{d,t}(a_t^n, b_t^i) < 0 \} \),
\( S_{dt,t} = S_{dt,t}(\psi_t, a_t^i) \cap S_{dt,t}(\psi_t, a_t^n) \),
\( W = F_{d,t}(a_t^d, b_t^i) - F_{d,t}(a_t^d, b_t^n) \)
\[ = \begin{cases} \arg \min_{b_t \in B_{1,t}(b_t^i)} \frac{F_{d,t}(a_t^d, b_t) - F_{d,t}(a_t^n, b_t^n)}{F_{d,t}(a_t^d, b_t^n) - F_{d,t}(a_t^n, b_t)}, & \text{if } C_1(b_t^i), \\
\arg \max_{b_t \in B_{2,t}(b_t^i)} \frac{F_{d,t}(a_t^d, b_t) - F_{d,t}(a_t^n, b_t^n)}{F_{d,t}(a_t^d, b_t^n) - F_{d,t}(a_t^n, b_t^n)}, & \text{if } C_2(b_t^i), \end{cases} \]
the condition \( C_1(b_t^i) = B_{1,t}(b_t^i) \neq \emptyset, B_{1,t}(b_t^i) = \emptyset, \) the condition \( C_2(b_t^i) = B_{2,t}(b_t^i) \neq \emptyset, \) and the set \( Q_d \) is defined in [2].

**Proof.** Since the attacker adopts mixed strategy in our problem, disconnection does not occur at stage \( t \) if \( q_{a_t} = 0 \) for every \( a_t \) in \( Z_d(b_t) \) i.e. the actions in \( Z_d(b_t) \) are dominated. In [19] Corollary 4, the conditions are derived for the case when a variable has a zero value in any optimal solution for a given linear program. Thus, by applying the conditions to each \( q_{a_t} \) in \( Z_d(b_t) \) our proposed linear program in [23], the result follows.

Proposition 4 shows that maintaining connectivity at each time epoch \( t \) depends on the payoffs of the attacker and the defender. Further, the payoff of the defender in (14) depends on the IoT network parameters. For example, the time required to deliver the information to the GS is a function of the IoT network capacity, as shown in the Appendix, which can be controlled by adjusting the transmission bandwidth in a wireless setting. Thus, the IoT operator, in order to maintain connectivity at each time epoch \( t \), can adjust its payoffs such that one of the conditions in Proposition 4 is met.

**VI. SIMULATION RESULTS AND ANALYSIS**

For our simulations, we consider an IoT network containing 1000 devices of 7 types: Type 1 corresponds to a radiological sensor, type 2 corresponds to a chemical sensor, type 3 corresponds to an infrared (IR) camera, type 4 corresponds to an explosives detector, type 5 corresponds to a surveillance camera, type 6 corresponds to a military robot containing a chemical sensor, a radiological sensor, an infrared camera and an explosives detector, and type 7 corresponds to a military unmanned vehicle containing a surveillance camera, an IR camera, a radiological sensor and a chemical sensor. The number of subareas considered is \( H = 5 \). The number of LSs available in each subarea is \( L_h = 2 \), the weight of each LS \( i \) is set to \( w_{L,i} = 15 \), which is chosen to be greater than the weight of any of the devices at a lower hierarchy level. The threshold on the number of sensors in each cluster \( D_{jh} \) is set to \( N_{bh,j} = 15 \). The normalizing coefficients are set to: \( \mu = 100, \nu = 1, \) and \( \lambda = 1 \). The costs of deploying a device of type \( \tau \) and an LS are set to be \( d_\tau = 0.5N_\tau \) and \( d_L = 50 \).

![Fig. 2: Probability of attacking the LS with the highest weight vs the cost of compromising an LS](image)

![Fig. 3: Probability of attacking the LS with the highest weight and the expected number of disconnected nodes respectively vs the cost of compromising an LS](image)

All normalization constants and costs values are chosen so that the costs are comparable to the number of sensors. For detailed analysis, the following scenarios are considered:

1) The cost of compromising an LS \( c_L \) is varied between 0 and 200 in steps of 50. The considered values of the cost \( c_{a_L} \) of determining the activated LS by the attacker are set to 0 and 100, respectively. The maximum number of stages considered is \( T = 1 \). The cost of determining the CH is set to be \( c_{CH} = 20 \) while the cost of compromising a device of type \( \tau \) is set to be \( c_\tau = 0.5N_\tau \).

2) The cost of finding the CH is varied between 0 and 100 in steps of 20. The costs of compromising an LS and determining the activated LS \( (c_{a_L}, c_L) \) are set to \( (300, 200) \) and \( (100, 50) \). The maximum number of stages considered is \( T = 1 \).

3) The maximum number of stages \( T \) is varied between 1 and 5 in steps of 1. The considered costs are \( c_{a_L} = 50, c_L = 50, c_\tau = 0.5N_\tau \) and \( c_{CH} = 20 \).

Fig. 2 shows, for both the FSE and and a baseline policy in which assigns equal probabilities to attacking the activated LSs, the probability of attacking the LS in the subarea with the highest weight as a function of the cost \( c_L \) of compromising an LS when the cost \( c_{a_L} \) of finding the activated LS is 0 or 100. Fig. 2 shows that, when \( c_{a_L} = 0 \), the FSE probability of attacking the activated LS in the subarea with the highest weight is 0.19 for \( c_L \) values less than 100. In this case, the payoff of attacking any activated LS is considerably higher than the payoff of attacking any other device device, and, thus, the attacker chooses to compromise only the five activated LSs, and the FSE mixed strategy of the attacker is comparable.
to the equal probability random policy. As $c_L$ increases to 150, the payoffs of attacking an activated LS and the CHs become comparable, and the attacker chooses to attack both the LSs and the CHs. Thus, the probability of attacking the LS with highest weight is reduced to 0.09. When $c_L$ increases further to 200, the payoff of attacking an activated LS becomes considerably lower than the payoff of attacking any of the CHs, and, thus, the attacker chooses to attack only the CHs. Next, for the case in which the cost of finding the activated LS is increased 100 with $c_L = 0$ the probability of attacking the activated LS is 0.19, which corresponds to the case in which the attacker chooses to attack only the LSs. From Fig. 2 we can also see that, for $c_L = 50$, the attacker chooses to compromise both the LSs and the CHs, and, thus, the probability drops to 0.09. For higher values of $c_L$, the payoff of attacking a CH becomes considerably higher than the payoff of attacking an LS. Thus, the probability of attacking an activated LS becomes zero.

Fig. 3 shows the expected number of disconnected sensors resulting from the FSE and the equal probability policy as function of the cost of compromising an LS when the cost $c_{aL}$ of finding the activated LS is 0 or 100. First, when $c_{aL} = 0$ and $c_L$ is less than or equal to 100, the expected number of disconnected sensors is 141 since the attacker chooses to compromise only the activated LSs. Also, the expected number of disconnected sensors is slightly higher than when the attacker chooses to attack each of the activated LSs with equal probability, since this policy is not optimal. Fig. 3 also shows that, for $c_L = 150$, the expected number of disconnected sensors decreases to 83 since the attacker chooses to compromise only the CHs. Thus, the value of the expected number of disconnected sensors of drops below the value of the equal probability random policy. When $c_L$ increases to 200, the expected number of disconnected sensors decreases to 62 since the attacker will now compromise CHs. In Fig. 4 we can see that, when $c_{aL} = 100$, the expected number of disconnected sensors is 141 when $c_L = 0$, since the attacker will choose to attack only the activated LSs. As $c_L$ increases to 50, the number of disconnected sensors decreases to 83, since the attacker choose to attack both the LSs and the CHs. For $c_L$ values higher than 100, the expected number of disconnected sensors becomes 62 since the attacker will be compromising only the CHs in this case.

Fig 4 shows the probability $p_{c_{\text{max}}}$ of attacking the CH of the cluster with highest number of sensors using the FSE versus the cost of finding the CH when the LSs costs are $(c_{aL}, c_L) = (300, 200)$ and $(c_{aL}, c_L) = (100, 50)$, respectively. When $(c_{aL}, c_L) = (300, 200)$ and $c_{CH}$ is less than or equal to 80, $p_{c_{\text{max}}}$ is 0.17. In this case, the payoff of attacking a CH is considerably higher than the payoff of attacking an LS or a device that is not a CH. Thus, the attacker will choose to compromise the CHs. When $c_{CH}$ increases to 100, the payoff of attacking a CH will be considerably lower than the payoff of attacking a device that is not a CH, and, thus, $p_{c_{\text{max}}}$ becomes zero. From Fig. 4 we can also see that, when $(c_{aL}, c_L) = (100, 50)$ and $c_{CH}$ is 0, the probability $p_{c_{\text{max}}}$ is 0.17 since the payoffs of attacking the CHs are the highest. As the value of $c_{CH}$ increases up to 40, the probability, $p_{c_{\text{max}}}$, decreases to 0.09 since the attacker chooses to compromise both the LSs and CHs. Then, the probability $p_{c_{\text{max}}}$ becomes zero as $c_{CH}$ increases up to 100 since the payoffs of compromising the CHs will be considerably lower than the payoffs of compromising the LSs, and the attacker will be compromising the LSs in this case. As for the equal probability policy, the probability of attacking a CH is zero since the attacker only compromises the activated LSs.

Fig. 5 shows, for both the FSE and the equal probability policy, the expected number of disconnected sensors versus the cost of finding the CH for LSs costs $(c_{aL}, c_L) = (300, 200)$ and $(c_{aL}, c_L) = (100, 50)$, respectively. When $(c_{aL}, c_L) = (300, 200)$ and for $c_{CH}$ values less than or equal to 80, the expected number of disconnected sensors is 63 since the attacker will be targeting the CHs in this case. As $c_{CH}$ increases to 100, the payoffs of attacking devices that are not CHs become considerably higher than the payoffs of attacking activated LSs and the CHs. Thus, the expected number of disconnected sensors decreases to 3.8. For LSs costs of $(100, 50)$, and when $c_{CH} = 0$, the expected number of disconnected sensors is 63 since the attacker will be compromising the CHs. Then, the expected number of disconnected sensors is 82 as the value of $c_{CH}$ increases to 40, since the attacker will choose proper (non-deterministic) mixed strategies over both the LSs and CHs. Then, as $c_{CH}$ becomes higher than 40, the expected number of disconnected sensors increases to 141 and exceeds the value of the equal probability random policy since the attacker will be compromising the activated LSs and the equal probability policy is not optimal.

Fig. 5 shows the expected number of disconnected sensors versus the maximum number of stages $T$ when FSE, the Stack-
elberg equilibrium with no feedback solution, and the equal probability policy are used, respectively. The Stackelberg equilibrium with no feedback solution corresponds to finding the Stackelberg equilibrium for a one stage game played at each time epoch $t$ $(1 \leq t \leq T)$. Using the three solutions, the expected number of disconnected sensors increases with the maximum number of stages. However, the expected number of disconnected sensors, when FSE is used, increase at a rate considerably slower than when either Stackelberg equilibrium with no feedback or the equal probability power policy are used. The decrease in the number of disconnected when using FSE reaches up to 57% compared to the equal probability policy and up to 62% compared to the Stackelberg equilibrium with no feedback, when $T$ is 5.

VII. CONCLUSION

In this paper, we have considered the connectivity problem in an Internet of Battlefield Things network in which an adversary attempts to cause disconnection by compromising one of the IoT nodes at each time epoch while a defender tries to restore the connectivity of the IoT by deploying new IoT nodes or changing the roles of nodes. We have formulated the problem as a multistage Stackelberg game in which the attacker is the leader and the defender is the follower. Due to the reliance of the attacker’s and the defender’s actions on the network state at each stage $t$, we have adopted the feedback Stackelberg equilibrium to solve the game. We have obtained sufficient condition to maintain connectivity at each stage $t$ when the FSE solution is used. Numerical results show that the expected number of disconnected sensors, when the FSE solution is used, decreases up to 62% compared to a baseline scenario in which a Stackelberg game with no feedback is used, and up to 57% compared to a baseline equal probability policy.

APPENDIX

APPENDIX:

EXPRESSSIONS OF PAYOFF FUNCTIONS

The expressions of $S_{D,t}(a_t, b_t)$, $A_t(a_t, b_t)$ in terms of each pair of the attacker’s and defender’s pure strategies $a_t$ and $b_t$ are given as follows.

- If $a_t = a_{t,i}$, $b_t = b_{t,j}k^*_t$,

$$S_{D,t}(a_t, b_t) = \sum_{h=1}^{H} \sum_{i=1}^{M} I(i \in D_h(t))(x_{ijh}(t)W_{jh}(t) + \bar{x}_{ijh}(t)))$$

$$A_t(a_t, b_t) = \max_{1 \leq h \leq H} z_h(t) \max_{1 \leq j \leq M} x(i \in D_h(t))$$

- $A_{D,t}(a_t, b_t) = \lambda D_{ijh}(t)$, $s_{ijh}(t)$ is the activated LS in subarea $h$, $W_{jh}(t)$ is given by $W_{jh}(t) = N_{jh}(t)$, $A_{D,t}(a_t, b_t)$ is the indicator function, $D_{ijh}(t)$ is a new indicator that is disconnected from the network, $Z_{ijh}(t)$ is an indicator if $D_{ijh}(t)$ is currently disconnected from the network, $\lambda D_{ijh}(t)$ is the time to transmit the information from cluster $N_{jh}(t)$ to LS $s_{ijh}(t)$ and is given by $A_{D,t}(f_{ijh}(t), s_{ijh}(t), D_{ijh}(t)) = \lambda (f_{ijh}(t), s_{ijh}(t)) +$
max_m∈D_j(t) Λ(n, f_jh(t)), Λ(f_jh(t), s_k(t)) is the time needed to transmit the information from CH f_jh(t) to LS s_k(t), (n, f_jh(t)) is the time needed to transmit the information from device n to CH f_jh(t), and Λ_p(s_k(t)) is the time required to deliver the information from s_k(t) to the GS. For any two IoT nodes i and j, Λ(i, j) is the single hop delay between i and j and is given by: Λ(i, j) = \frac{R_{ij}}{C_{ij}} where R_{ij} is the capacity of the link (i, j) and m_i is the packet size of node i.

- If \( a_i = a_d, i, b_i = b_d, j, i \in D_j(t) \),

\[ S_{D_j}(a_t, b_t) = \sum_{i=1}^{M} I(i \in D_j(t))x_{ijh(t)}W_{jh(t)} + x_{ijh(t)}, \]

\[ \Lambda_t(a_t, b_t) = \max_{1 \leq h \leq H} \left( I(h = h')\sum_{i=1}^{M} I(i \in D_j(t))I(f_{jh}(t) \neq i) \right. \]

\[ \times(I(j \notin H_k)\sum_{i=1}^{M} I(i \in D_j(t))I(f_{jh}(t)) + \Lambda_p(s_k(t))) + \right) \]

\[ + I(i \notin H_k)\sum_{i=1}^{M} I(i \in D_j(t))I(f_{jh}(t)) + \Lambda_p(s_k(t)) \]

where D_j(t) is the set of devices in subarea A_h, \( D_j^c(t) = D_j(t) \cup \{ N(t) + 1 \} \), and N(t) + 1 is the index of the newly deployed device and N(t) is the total number of devices.

- If \( a_t = a_d, i, b_t = b_d, j, i \in D_j(t) \),

\[ S_{D_j}(a_t, b_t) = \sum_{i=1}^{M} I(i \in D_j(t))x_{ijh(t)}W_{jh(t)} + x_{ijh(t)}, \]

\[ \Lambda_t(a_t, b_t) = \max_{1 \leq h \leq H} \left( I(h = h')\sum_{i=1}^{M} I(i \in D_j(t))I(f_{jh}(t) \neq i) \right. \]

\[ \times(I(j \notin H_k)\sum_{i=1}^{M} I(i \in D_j(t))I(f_{jh}(t)) + \Lambda_p(s_k(t))) + \right) \]

\[ + I(i \notin H_k)\sum_{i=1}^{M} I(i \in D_j(t))I(f_{jh}(t)) + \Lambda_p(s_k(t)) \]

where W_{jh}(t) is given by: \( W_{jh}(t) = \sum_{i=1}^{M} I(i \in D_j(t))w_i + w_{L,h}, \)

- If \( a_t = a_d, i, b_t = b_{L,h}, \)

\[ S_{D_j}(a_t, b_t) = \sum_{i=1}^{M} I(i \in D_j(t))x_{ijh(t)}W_{jh(t)} + x_{ijh(t)}, \]

\[ \Lambda_t(a_t, b_t) = \max_{1 \leq h \leq H} \left( I(h = h')\sum_{i=1}^{M} I(i \in D_j(t))I(f_{jh}(t) \neq i) \right. \]

\[ \times(I(j \notin H_k)\sum_{i=1}^{M} I(i \in D_j(t))I(f_{jh}(t)) + \Lambda_p(s_k(t))) + \right) \]

\[ + I(i \notin H_k)\sum_{i=1}^{M} I(i \in D_j(t))I(f_{jh}(t)) + \Lambda_p(s_k(t)) \]

The expressions of \( C_{a_t}(a_t, b_t) \) and \( U_{D_d}(a_t, b_t) \) in terms of the pure strategies of the attacker and the defender are given as follows:

\[ C_{a_t}(a_t, b_t) = \begin{cases} c_1, & \text{if } a_t = a_d, i \text{, } b_t = b_{L,h}, \\ c_2, & \text{if } a_t = a_d, i \text{, } b_t = b_{d,kh}, \end{cases} \]

\[ C_{d}(a_t, b_t) = \begin{cases} d_1, & \text{if } b_t = b_d, k, h \text{, } b_t = b_{L,h}, \\ d_2, & \text{if } b_t = b_{d,kh}, \\ 0, & \text{otherwise}. \end{cases} \]

The expression of the defender’s utility is given by

\[ U_{D_d}(a_t, b_t) = \begin{cases} u_1, & \text{if } b_t = b_d, k, h \text{, } b_t = b_{L,h}, \\ u_2, & \text{if } b_t = b_{d,kh}, \\ 0, & \text{otherwise}. \end{cases} \]