

# An Evolutionary Game-Theoretic Framework for Cyber-threat Information Sharing

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**Abstract**—The initiative to protect against future cyber crimes requires a collaborative effort from all types of agencies spanning industry, academia, federal institutions, and military agencies. Therefore, a Cybersecurity Information Exchange (CYBEX) framework is required to facilitate breach/patch related information sharing among the participants (firms) to combat cyber attacks. In this paper, we formulate a non-cooperative cybersecurity information sharing game that can guide: (i) the firms (players)<sup>1</sup> to independently decide whether to “participate in CYBEX and share” or not; (ii) the CYBEX framework to utilize the participation cost dynamically as incentive (to attract firms toward self-enforced sharing) and as a charge (to increase revenue). We analyze the game from an evolutionary game-theoretic strategy and determine the conditions under which the players’ self-enforced evolutionary stability can be achieved. We present a distributed learning heuristic to attain the evolutionary stable strategy (ESS) under various conditions. We also show how CYBEX can wisely vary its pricing for participation to increase sharing as well as its own revenue, eventually evolving toward a win-win situation.

**Index Terms**—Cybersecurity, CYBEX, Evolutionary Game Theory, Incentive Model, Information Sharing

## I. INTRODUCTION

A robust cybersecurity information sharing infrastructure is needed to protect a firm’s confidential information from future cyber attacks. This can be difficult to achieve via sole effort [1]. The executive orders from the U.S. federal government clearly encourage firms to share their cybersecurity breach and patch related information with other firms to strengthen the nation’s security infrastructure. Among recent cyber attack victims are, well-known retail shops, Target Corp, and Neiman Marcus. Their breaches were reported [2] as payment card numbers, personal information of approximately 70 million customers. Cyberattack on JP Morgan Chase & Co. [3] reportedly compromised the accounts of 76 million households and 7 million small businesses. Disclosure of this attack information to public resulted a drop in its stock price to 0.9% and lost 1.3% of its value. Thus, rising rate of cyber crimes can dramatically affect the revenue of firms; therefore,

a significant amount of resources are being invested for developing cyber defenses to combat criminal cyber attacks.

Isolated research on cybersecurity threat analysis and individually developed anti-threat strategies may not be a cost-effective way to tackle cyber crimes [4]. For instance, when a firm finds it has been compromised by an attacker, it usually immediately invests time and money to develop a countermeasure. At the same time, another organization that had previously faced a similar attack would already have developed a countermeasure for the breach. Incentivized exchange of firms’ vulnerability information, proactive security breaches, successful/unsuccessful breach or patch information etc., can be an effective way for firms to collaboratively [5] improve their security infrastructure with efficient technology investment. However, currently the firms hesitate to share their security information with other organizations including federal agencies due to the following reasons: (1) negative publicity might affect their market value and stock price; (2) sharing of security holes with competing firms can be risky if rivals violate trust and take advantage of the breach reporting firm directly or indirectly with the help of third-party agents. The current practice of using isolated cybersecurity mechanisms can be highly expensive yet mostly ineffective against the ever-changing tactics of cyber attackers.

A departure from this unpromising practice is seen in the concept of the Cyber Security Information Exchange (CYBEX) network and is being investigated by network and cybersecurity personnel, policy makers, governments and economists to enable the security information sharing. ITU-T (International Telecommunication Union-Telecommunication) took the initiative to adopt CYBEX [6] to tighten cybersecurity and infrastructure protection. The CYBEX framework aims to provide a service of structured information exchange about measurable security states of systems/devices together with incidents stemming from cyber attacks. One major challenge is that the architecture of the CYBEX assumes the firms to be always cooperative with each other; however, the inescapable fact remains that firms compete with each other. They compete for: more revenue, market share, and shareholders. This competition is distributed and highly non-cooperative. Therefore, devising self-enforcement mechanisms for the firms to participate in the information sharing framework is necessary,

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<sup>1</sup>The words “players”, “participants” and “firms” are used interchangeably throughout this paper unless they are explicitly mentioned otherwise.

## Report Documentation Page

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which will maximize the social welfares of both participants as well as CYBEX and security robustness of the firms. On the other hand, as CYBEX aims to maximize its revenue through participation cost, it is important to study how CYBEX can vary its pricing for participation to increase sharing as well as its own revenue, thus evolving toward a win-win situation.

Due to limited academic literature on incentives or participation costs, there is little or no understanding of the effectiveness of dynamic participation cost on information sharing as an incentive/deterrence to induce firms' behavior. This underscores the question: how much incentive/participation costs should be induced and when, to motivate the firms to participate in the CYBEX, yet make the sharing system self-dependent and self-enforced so that sharing is done directly rather than through external means only? Under such dynamic cost adjustment of CYBEX, the firms must figure out their optimal strategies ("participate & share" or not) to play with so that they maximize their expected payoff. One very important objective in this regard is the existence of the evolutionary stable strategy (ESS) [7][8] from the firms' perspective in such evolutionary games. ESS is a strategy which, if adopted by a population of players, cannot be invaded by any alternative strategy. We aim to orchestrate the opportunistic CYBEX self-coexistence game for achieving ESS, where the players are adaptive, dynamically evolving and most importantly playing in an uninformed non-cooperative setting.

The rest of the paper is organized as follows. The components of the CYBEX self-coexistence game are described in Section II. Section III formalizes and analyze the game to find the conditions under which ESS can be achieved. The insights for CYBEX and the proposed distributed learning heuristic is also detailed in this section. Section IV presents results achieved via simulation. Section V concludes the paper.

## II. CYBEX SELF-COEXISTENCE GAME FORMULATION

In this work, we consider the generic abstraction of "always rational and profit-seeking" firms. We consider a market scenario, where there are  $N$  firms playing independently in this game and trying to decide whether to participate in the CYBEX framework and share with other firms by incurring a participation cost. From CYBEX point-of-view, the decision problem is how much incentive/participation costs should be induced and when, to motivate the firms to participate in the CYBEX framework. If CYBEX charges too high to increase its revenue, the firms may possibly get deterred from participation, eventually reducing CYBEX's revenue. On the other hand, if CYBEX charges too low to attract firms, the revenue generated by CYBEX might be insufficient to sustain in the market. Thus it is important to investigate, under what conditions and how CYBEX can dynamically decide on incentive/participation cost to attract increasing number of participants to share (which will increasingly strengthen their cyber-defense capability), yet increase CYBEX's revenue. To model the firms' payoff, the following two components are considered in this work.

### A. Sharing and Investment Gain

Assuming the firms invest for their own cybersecurity R&D, the firm directly benefits from its own investment. Additionally, an indirect reflected gain is received from the other firms' shared information, which can produce proactive defense, patches and fixes. Therefore, exchange of this valuable information with other firms improves their overall utility. Though participating in CYBEX and sharing information is beneficial for protecting the firms' assets from cyber criminal activities, the participation in the CYBEX architecture and sharing information among the firms are not cost-free.

### B. Modeling Costs in CYBEX

There exists a cost of participation in the CYBEX architecture, which is defined by the cost that the CYBEX charges the firms for maintenance as well as certification (for sharing). Apart from the participation cost, there also exists a cost of information sharing, which has two parts: retrieving the information for relevance, and the potential loss of reputation. Therefore, self-enforcement schemes need to be devised to motivate and attract the firms to participate and share in CYBEX framework.

## III. ANALYZING CYBEX SELF-COEXISTENCE GAME

Once the problems are identified and the game is formalized, we need to solve the game for the firms. Solving a game means predicting the steady state strategy of each player assuming they are rational. One can see that if the strategies from the players are mutual best responses to each other, no player would have a reason to deviate from the given strategies and the game would reach ESS.

In this section, we now analyze the CYBEX self-coexistence game in-depth and investigate if the game has ESS and under what conditions. We are particularly interested in modeling incentive/participation cost which can be used as an initial incentive to attract the firms to share in the CYBEX framework. The system is aimed to be independent and self-enforced, so that the information sharing nature of firms is enhanced even without any external stimulant, which will help the system to reach ESS in a self-enforced manner. As far as a decision strategy in this game model is concerned, every firm has the binary strategy set:

$$\mathbb{S} = \{\text{Participate and Share in CYBEX, Not Participate}\}$$

With the strategy set defined, we now define the pairwise strategic form payoffs in Table I, when any two of the firms engage in pairwise interaction.

	Participate & Share	Not Participate
Participate & Share	$Sa \log(1+I) - x - c,$ $Sa \log(1+I) - x - c$	$a \log(1+I) - x - c,$ $a \log(1+I)$
Not Participate	$a \log(1+I),$ $a \log(1+I) - x - c$	$a \log(1+I),$ $a \log(1+I)$

TABLE I: Strategic-form payoffs

When firms are not involved in the CYBEX framework (i.e., they neither participate nor share), the utility reward to the firms is dependent on only their own investment, which can be presented as the following variant of logarithmic function,  $a \log(1+I)$ , where  $I$  is the amount of investment

made by the firms and  $a$  is a simple scaling parameter that maps user satisfaction/benefit to a dimension equitable to the price/monitory value. For the rationality constraint, we assume  $a \log(1 + I) > 0$ , otherwise, the firms would prefer to not make any investment. The logarithmic gain function motivates the players by rewarding for increasing steps towards security investment. However the reward eventually saturates with gradually increasing investment. This is because increasing the investment further even beyond a certain threshold does not necessarily increase the overall utility with a high rate of increment, rather limiting and saturating the reward obtained. In this symmetric game work, we assumed a fixed investment  $I$  from every firm. In our future work of asymmetric CYBEX self-coexistence game, we will also assume different investment values from the firms.

We also assume, when both the engaged firms participate in mutual sharing, the resulting benefit for them would then stem, not just from their own investment, but also from their sharing. Thus we consider this utility (when both the firms sharing mutually) as  $Sa \log(1+I)$ , which can be considered as return on both investment and sharing. Again for the rationality constraint,  $S > 1$ , otherwise the player does not have any incentive of sharing.  $c$  is the cost of participation in the CYBEX framework, i.e., the amount charged by CYBEX for participating and  $x$  reflects the cost of information sharing as explained earlier in Subsection II-B.

However, when a pair of firms are mutually interacting, while one of them is part of CYBEX and the other is not, then the utility to the firms are given in the top right corner and bottom left corner cells. This scenario depicts the risk of participating, where the participating firm incurs the cost due to participation in CYBEX without any additional sharing gain and the other non-participating firm incurring no cost but also not gaining anything due to not sharing. Note that, we could always use any other complex values or functions for depicting the utilities and cost, however, our aim here is to analyze the ESS and its conditions in the game regardless of the exact utility or cost values as long as the nature of utility and the costs follow the rationality constraints as required in a real market. For the ESS analysis, we modeled this game as a symmetric game and derive various conditions under which different ESS can be achieved by the group of players.

To analyze the evolutionary stability of the game, we assume  $\alpha \in [0, 1]$  is the proportion of population participating and sharing in CYBEX. Then, according to replicator dynamics [7][8], the transformation speed can be given by

$$g(\alpha) = \alpha[E_u(sh) - E_p] \quad (1)$$

where,  $E_u(sh)$  is the expected payoff of a player  $u$  for participating and sharing, and  $E_p$  is the average payoff in the population. The expected utility of “participate & share” strategy can be given as

$$E_u(sh) = \alpha[Sa \log(1+I) - x - c] + (1-\alpha)[a \log(1+I) - x - c]$$

Similarly,  $E_u(not)$  is the expected payoff of a player for not sharing, where  $E_u(not) = a \log(1 + I)$ . Hence,

$$E_p = \alpha[E_u(sh)] + (1 - \alpha)[E_u(not)]$$

After simplifications, the replicator equation given in Eqn. (1) can be rewritten as:

$$g(\alpha) = \alpha(1 - \alpha)[\alpha(S - 1)a \log(1 + I) - x - c] \quad (2)$$

For ESS to be achieved, there are two conditions [7], [8]: (1) the transformation rate should be zero, i.e.,  $g(\alpha) = 0$ , and (2) the neighborhood of the equilibrium states (found through condition (1)) must also be stable. To prove a strategy to be evolutionarily stable, it is necessary to verify that the population playing with ESS cannot be invaded by any other individual(s) playing with strategy other than ESS. If condition (2) is not met, then there is a chance that any small subgroup of player playing with a random strategy other than ESS can invade the total population of players playing ESS.

For the transformation rate to be zero, i.e.,  $g(\alpha) = 0$ , there exists three distinct solutions of  $\alpha$ , (i.e., three potential equilibrium states):

$$\alpha_{sol_1} = 0, \alpha_{sol_2} = 1, \text{ and } \alpha_{sol_3} = \frac{x + c}{(S - 1)a \log(1 + I)}$$

With these three potential equilibrium states, we now need to check the stability of their neighborhood and then only the equilibrium states can be recognized as ESS. For the neighborhood to be stable, the condition of  $g'(\alpha) < 0$  must hold true at each of the equilibrium states. With the three solutions of  $\alpha$ , it is found that

$$g'(\alpha_{sol_1}^* = 0) = -x - c$$

$$g'(\alpha_{sol_2}^* = 1) = -(S - 1)a \log(1 + I) + x + c$$

$$g'(\alpha_{sol_3}^* = \alpha_{sol_3}) = (x + c) - \frac{(x + c)^2}{(S - 1)a \log(1 + I)}$$

Therefore it is clear that ESS is conditioned upon the wise choice of the incentive/participation cost ( $c$ ) and it can be used to motivate the socially optimal behavior and deter non-cooperative behaviors. Next, we analyze the conditional constraints and show under what bounds the population will evolve toward sharing and under what bounds they would not.

#### A. Analyzing conditional constraints for ESS

As can be seen in the following, we analyze all possible conditional constraints for ESS, depending on the incentive/participation cost ( $c$ ), governed by the CYBEX system for governance. Note that, the cost of information exchange,  $x > 0$  as this is an inherent cost for information sharing.

**Case (i):** Let us first assume,  $c > 0$  &  $c \geq (S - 1)a \log(1 + I)$ . Therefore,  $g'(\alpha_{sol_1}^* = 0) < 0$  and  $g'(\alpha_{sol_2}^* = 1) > 0$ .

It can be seen that  $g'(\alpha_{sol_3}^*)$  itself does not hold as  $\alpha_{sol_3}^* > 1$  as it must lie between 0 and 1. Hence  $\alpha_{sol_1}^* = 0$  is the only ESS under this condition, which implies that ESS for the population would be to “not participate” in the CYBEX architecture due to high cost for such activity. Though it is intuitive that the population will never participate in the sharing framework because of high participation cost ( $c$ ), this cost has an important role in motivating the players to participate, which is discussed in the later case. For numerical analysis, we show a simple scenario following the above conditions even when the evolutionary game initiates from a

high “participate & share” population proportion  $\alpha^* = 0.8$ , it is found from Fig. 1(a) that the individuals taking “Not Participate” strategy could successfully invade the individuals that are participating and sharing because of no cost for taking “Not Participate” strategy. For all the results found from numerical analysis, we assumed the rationality constant  $S = 2$ ; scaling constant  $a = 3$ ; and investment ( $I$ ) as 5 units. The values of participation cost ( $c$ ) and cost of information sharing ( $x$ ) are suitably varied for different cases based on each condition. For this case, we assumed  $c = 7.4$ , and  $x = 3$ .

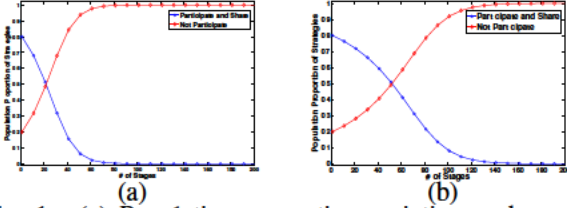


Fig. 1: (a) Population proportion variation under constraint (i), (b) Population proportion variation under constraint (ii)

**Case (ii):** When  $c > 0$  &  $c < (S - 1)a \log(1 + I)$  such that  $(c + x) \geq (S - 1)a \log(1 + I)$ . Therefore,  $g'(\alpha_{sol_1}^* = 0) < 0$  and  $g'(\alpha_{sol_2}^* = 1) > 0$ .

It can be seen that  $g'(\alpha_{sol_3}^*)$  itself does not hold true, as  $\alpha_{sol_3}^*$  does not lie between 0 and 1. Thus,  $\alpha_{sol_1}^* = 0$  is the only ESS implying the population still will not choose to participate in the CYBEX regardless of the initial proportion of participating population. As the total cost exceeds the sharing gain, the initial population taking the “Participate and Share” strategy can easily be invaded by a small group of individuals taking the “Not Participate” strategy. The result from numerical analysis is presented in Fig. 1(b) by assuming  $c = 3.4$  and  $x = 3$ , which demonstrates that irrespective of any initial  $\alpha$  value, the ESS is always found to be “Not Participate” strategy and always gets invaded by the population of “Participate and Share” strategy.

**Case (iii):** When  $c > 0$  &  $c < (S - 1)a \log(1 + I)$  such that  $(c + x) < (S - 1)a \log(1 + I)$ . Therefore,

$$g'(\alpha_{sol_1}^* = 0) < 0, \quad g'(\alpha_{sol_2}^* = 1) < 0$$

$$g'(\alpha_{sol_3}^*) = (c + x) \left[ 1 - \frac{c + x}{(S - 1)a \log(1 + I)} \right]$$

It is clear that  $g'(\alpha_{sol_3}^*) > 0$ . Hence, two possible ESS ( $\alpha_{sol_1}^* = 0$  and  $\alpha_{sol_2}^* = 1$ ) exist in this case, however achieving a particular ESS depends on the initial “participate and share” population distribution. ESS tends to “Not Participate” if  $0 < \alpha^* < \frac{c+x}{(S-1)a \log(1+I)}$  and ESS tends to “Participate and Share” if  $\frac{c+x}{(S-1)a \log(1+I)} < \alpha^* < 1$ , where  $\alpha^*$  is the initial population fraction playing with participate and share strategy. This clearly implies that if the initial “Participate & Share” population fraction is more than a certain threshold/tipping value,  $\alpha_{thres} = \frac{c+x}{(S-1)a \log(1+I)}$ , then the rest of the population fraction (which are not sharing) will evolve over time and will participate in CYBEX, thus ESS tends toward “Participate and Share” strategy. Alternatively, if the initial “Participate & Share” population fraction is less than  $\alpha_{thres}$ , then the gain from the system would not be sufficient enough to enforce the

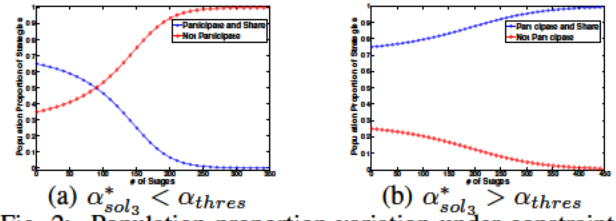


Fig. 2: Population proportion variation under constraint (iii)

entire population toward sharing rather ESS will tend towards “Not Participate” strategy, thus showing the significance of the initial “Participate and Share” population strength as well as the significance of incentive/participation cost ( $c$ ). Fig. 2 presents two sample numerical results where the initial population proportion of “Participate and Share” strategy  $\alpha^* = 0.65$  and  $0.75$  respectively, assuming  $c = 2.4$ ,  $x = 1.5$ . The simulation results validate the deflecting nature of ESS based on the theoretical threshold/tipping value that can be computed numerically by using the  $\alpha_{thres}$  expression, and found to be 0.72. From Fig. 2(a), it is shown that most individuals lean towards the “Not Participate” strategy, when the initial participating population proportion  $\alpha^*$  is below the threshold value. However, when the initial “Participate and Share” population is above the threshold value, the population evolves towards more participation as shown in Fig. 2(b). The expected individual utility is the reason for such deflection in ESS because the average utility to a firm playing “Not Participate” strategy is more, when the proportion of players playing the same strategy is low, compared to the complement strategy and vice versa.

**Case (iv):** When  $c < 0$  such that  $(c + x) \leq 0$ , i.e., the cost of participation is negative implying the fact that it is no longer a cost but rather a positive incentive given to the firms for enrolling in CYBEX architecture. Therefore,  $g'(\alpha_{sol_1}^* = 0) > 0$  and  $g'(\alpha_{sol_2}^* = 1) < 0$ .

It is clear that  $g'(\alpha_{sol_3}^*)$  itself does not hold true. Hence  $\alpha_{sol_1}^* = 0$  is the only ESS under this condition, which implies that ESS for the population would be to participate and share in the CYBEX architecture regardless of initial  $\alpha^*$  value. According to this case, the total cost ( $c + x$ ), appears to be an incentive for firms to participate, hence the population will eventually be inclined towards the “Participate & Share” strategy irrespective of any  $\alpha^*$  value as shown in Fig. 3, where  $c + x$  is assumed to be -1. The result shows that the individuals with “Participate and Share” strategy could successfully invade the “Not Participate” strategy individuals.

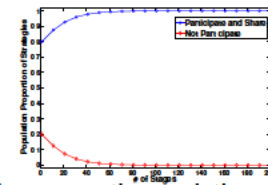


Fig. 3: Population proportion variation under constraint (iv)

#### B. Understanding the impact of conditional constraints

**Guidance for CYBEX:** The above discussion illustrates how the evolutionary stability structure of CYBEX is directly dependent on the incentive/participation cost along with initial

sharing population strategies. Thus it is of utmost importance to model this incentive/cost according to the conditional constraints presented in above to establish and maintain an effective CYBEX sharing system. These conditions not only show that ESS can be achieved, but also demonstrate how the participation cost is a factor for information exchange and the utility obtained through sharing. At the start of the game, if the initial “participating” population is completely dispersed and there is no enrollment in the CYBEX architecture, our analysis shows that using case (iv), incentives can be given to help and evolve the system toward mutual sharing rather than charging cost of participation. Once the system goes beyond the threshold (in terms of number of players enrolled in CYBEX), then moving into case (iii), would still ensure that the system will now self-enforce in sharing without any external positive incentive. Then the cost of participation can be used according to the case (iii) above, which will keep the system stable and self-enforced to share even without any external incentive. The nature of the firms sharing would reciprocate the rest of the firms thus evolving toward a cooperative ESS.

### C. Learning heuristic for evolutionary stable strategy

Earlier, we presented the detailed theoretical analysis and impact of conditional constraints for ESS, which outlines how CYBEX should dynamically induce the participation cost/incentive to attract and self-enforce firms toward sharing and achieve stability. However, in a distributed non-cooperative information sharing game, it is also necessary to design a learning heuristic for the firms to decide which strategy to play at each stage, and how to update their “strategy selection probability” based on the utility feedback obtained from the past game stages.

Now, we present the distributed learning algorithm for the firms to reach ESS. For choosing a strategy based on the firms’ past experience, each firm  $i \in \mathcal{N}$ , maintains a probability vector,  $p^{(i)}(t) = \{(p_1^{(i)}(t), p_2^{(i)}(t)) : p_1^{(i)}(t) + p_2^{(i)}(t) = 1\}$ , which defines the probability of choosing “Participate & Share” and “Not Participate” strategy at game stage  $t$  respectively. In each stage, all possible pairwise simultaneous interactions are conducted from each firm’s perspective, where, each firm  $i \in \mathcal{N}$  sticks to a single strategy throughout the stage and observes the average pairwise utility  $\bar{U}_{pair}^{(i)}(t)$  for stage  $t$ , which is given by:  $\bar{U}_{pair}^{(i)}(t) = \frac{\sum_{j \neq i} U_i^{(t)}(s_i, s_j)}{|\mathcal{N}|-1}$  where,  $U_i^{(t)}(s_i, s_j)$  is the payoff to player  $i$  from the simultaneous pairwise game between firm  $i$  and  $j$  by playing with strategy  $s_i$  and  $s_j$  respectively at game stage  $t$ .

After each game stage, the player  $i$  updates its probability of selecting strategy  $s_i$  by utilizing two different average utility vectors: (1)  $\bar{U}_{avg}^{(i)}(t)$ : average received utility, and (2)  $\bar{U}_{s_i \in S}^{(i)}(t)$ : average utility obtained by playing “strategy  $s_i$  only” until stage  $t$ , which are defined as follows:

$$\bar{U}_{avg}^{(i)}(T) = \frac{\sum_{t=1}^T \bar{U}_{pair}^{(i)}(t)}{T} \quad (3)$$

$$\bar{U}_{s_i \in S}^{(i)}(T) = \frac{\sum_{t=0}^T \{\bar{U}_{pair}^{(i)}(t) | a_i(t) = s_i\}}{T'} \quad (4)$$

where,  $a_i(t)$  is the action of player  $i$  at game stage  $t$  and player  $i$  played strategy  $s_i$  for  $T'$  number of stages until stage  $T$ , such that  $T' \leq T$ .

To learn a stable strategy from the strategy set  $S$ , the probability of choosing a particular strategy must be reflected from the average utility it receives by playing that strategy. Hence the difference between player  $i$ ’s average utility obtained by playing a particular strategy  $s_i$  and average utility out of all game stages will help to decide the probability of choosing  $s_i$  in future. Assuming player  $i$  played strategy  $s_i \in S$  at  $(t-1)^{th}$  stage, the probability of playing the same strategy ( $p_{s_i}^{(i)}(t)$ ) at  $t^{th}$  stage can be computed using the update rule.

$$p_{s_i}^{(i)}(t) = p_{s_i}^{(i)}(t-1) + \kappa(\bar{U}_{s_i}^{(i)}(t) - \bar{U}_{avg}^{(i)}(t)) \quad (5)$$

where,  $\kappa \in (0, 1)$  represents the learning constant that determines how fast or slow the players will move towards the optimal probability of choosing a particular strategy. The probability of playing with complementary strategy ( $s'_i$ ) can be given as:  $p_{s'_i}^{(i)}(t) = 1 - p_{s_i}^{(i)}(t)$ . The Algorithm 1 summarizes the distributed learning heuristic.

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#### Algorithm 1: Learning Heuristic for ESS Convergence

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- 1 Initialize the initial “sharing” population proportion  $\alpha(0)$  for “Share” strategy, and utility matrix  $U$ ;
  - 2 Initialize random strategy profile,  
 $p^{(i)}(0) = (p_1^{(i)}(0), 1 - p_1^{(i)}(0)) \forall i \in \mathcal{N}$  ;
  - 3 **for** stage  $t = 1$  to  $MaxT$  **do**
  - 4     **for** each firm  $i \in \mathcal{N}$  **do**
  - 5         Select a strategy  $s_i \in S$  based on its mixed strategy profile  $p^{(i)}(t)$ ;
  - 6         Observe the average utility reward  $\bar{U}_{pair}^{(i)}(t)$  from all simultaneous pairwise interactions;
  - 7         Update the probability of selecting strategy  $s_i$  ( $p_{s_i}^{(i)}(t+1)$ ) for player  $i$  according to equation 5;
  - 8         Update the probability of playing with complementary strategy  $s'_i$  as  $(1 - p_{s_i}^{(i)}(t+1))$ ;
  - 9     **end**
  - 10 **end**
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## IV. EXPERIMENTAL RESULTS

In this section, we present the simulation results for our proposed mechanism assuming the population size as 100, rationality constant  $S$  and investment  $I$  as 2, and 5 units respectively, which are kept same for all the experiments. The values of  $x$  and  $c$  are varied dynamically to maintain different conditions described in Section III. The learning constant ( $\kappa$ ) is assumed to be 0.07. Each stage represents all the possible simultaneous pairwise interactions between the players, and they play 500 such stages in each experiment. Unless otherwise mentioned, the initial “Share” strategy population proportion is considered as 65%.

In Fig. 4(a), we plot the evolution of average utility over the number of stages for different cost ( $c$ ) values. It is



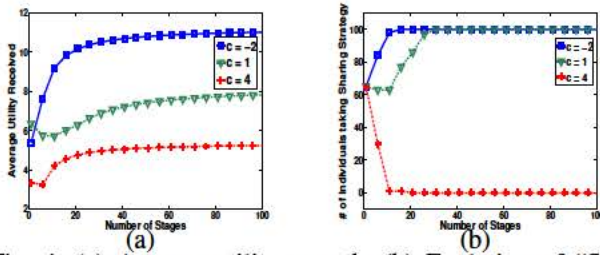


Fig. 4: (a) Average utility growth, (b) Evolution of “Share” strategy population under different participation cost

observed that when the cost of participation ( $c$ ) is negative, the individuals find an incentive to participate and share. However, when  $c > 0$ , the individuals choose to take part and share in the framework opportunistically depending on how many other players participate and share in the framework. Therefore, the average utility converges at high value when the participation cost is minimum, where the population unanimously play the “Participate & Share” strategy. As  $c$  increases above certain threshold, the individuals find that participating in sharing is costly and switch to “Not Participate” strategy, which is why the saturated average utility is less for  $c = 4$  than 1. It is shown that the proposed heuristic helps the individuals reach the evolutionary stable state within fewer game stages by making them learn about the expected utilities of different strategies. We experimented to understand how quickly the population adapts to ESS, we plot the growth of “Share” strategy population in Fig. 4(b). It is clear that a population type either invades another type or gets invaded by the other type depending on the cost constraints. If the participation cost ( $c$ ) is negative, then it is intuitive that everybody will be willingly participate and share because the participation cost is nothing but an incentive. However, when the cost is positive, then the stable strategy depends on how many other members adopt that particular strategy. In our experimental setup, the population converge to “Participate and Share” when the initial sharing strategy population is 65% or more and cost ( $c$ ) is 1, but they get invaded by the rest of “Not Participate” strategy individuals if  $c$  increases to 4 because the tipping point requirement is now well above 65%. The important point to notice here is the convergence speed of the proposed learning heuristic, which enables the firms to obtain their ESSs within very few number of game stages.

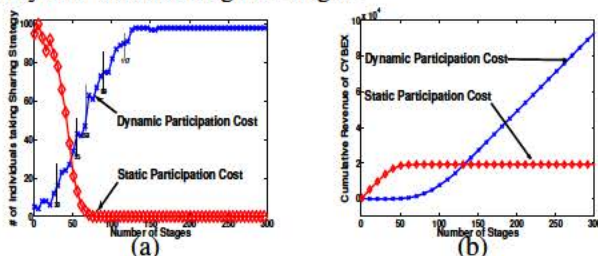


Fig. 5: (a) Dynamics of “Participate and Sharing” Population under static and proposed dynamic participation cost, (b) CYBEX’s gross revenue comparison under static and proposed dynamic participation cost charged by CYBEX

To understand how our proposed dynamic participation cost/incentive can help CYBEX to increase its revenue, we

simulate two scenarios presented in Fig. 5(a): where (1) 95% individuals initiated with “participate and sharing” strategy in the beginning but CYBEX charges a fixed amount ( $c = 5$ ) towards participation all along, and (2) CYBEX uses our proposed dynamic participation cost/incentive mechanism (as per the steps provided in Section III(B)), even when only 5% of total population were sharing at starting. It is observed that in the scenario (1), the participating population percentage decreases over stages due to the high cost charged by CYBEX (as seen in Fig. 5(a), in red color plot). It is also seen that the cumulative revenue of CYBEX over time does not increase constantly as firms leave the framework gradually (as seen in Fig. 5(b), in red color plot). However in scenario (2), CYBEX could manage to attract more firms to participate by rewarding ( $-c = 0.5$ ) them in the beginning. As the number of participants started growing (going beyond the population threshold/tipping point given in case (iii), Section III), CYBEX dynamically updates its participation cost within a certain limit (based on the cost conditions presented in case (iii)) to generate revenue. But it ensures that the cost raise do not lead the firms to leave the framework rather it can still attract more participants to join so that eventually every firm will be inside the sharing framework. Thus CYBEX’s incremental cost raise can lead to a win-win situation, where every firm participates and shares to strengthen their security infrastructure, and CYBEX also generate an increasing revenue as depicted in Fig. 5(a), and (b) respectively (blue color plots).

## V. CONCLUSIONS

In this research, we studied evolutionary game model to understand how competing firms in a non-cooperative game can decide independently to participate in the CYBEX and share or not. Considering the cost of participation in CYBEX, in addition to the cost of sharing, we derived the conditions under which ESS can be achieved. We proposed a distributed learning heuristic which lead the firms towards ESS. We also showed that how CYBEX can wisely vary its incentive or participation cost by the firms to increase sharing which in turn increases its own revenue, eventually evolving toward a win-win situation.

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