Game Theoretic Study on Blockchain Based Secure Edge Networks

Dongjin Xu*, Liang Xiao*, Limin Sun†, Min Lei‡
* Dept. of Communication Engineering, Xiamen University, China. Email: lxiao@xmu.edu.cn
† Beijing Key Laboratory of IOT Information Security Technology, Institute of Information Engineering, CAS, China.
Email:sunlimi@iie.ac.cn
‡ Information Security Center, Beijing University of Posts and Telecommunications, China
Email:leimin@bupt.edu.cn

***Abstract*—Blockchain has been applied to study data privacy and network security recently. In this paper, we propose a punishment scheme based on the action record on the blockchain to suppress the attack motivation of the edge servers and the mobile devices in the edge network. The interactions between a mobile device and an edge server are formulated as a blockchain security game, in which the mobile device sends a request to the server to obtain real-time service or launches attacks against the server for illegal security gains, and the server chooses to perform the request from the device or attack it. The Nash equilibria (NEs) of the game are derived and the conditions that each NE exists are provided to disclose how the punishment scheme impacts the adversary behaviors of the mobile device and the edge server.**

***Index Terms*—Blockchain, edge network, game theory, network security.**

I. Introduction

The real-time mobile applications such as augmented reality and gaming applications require the low-delay mobile services to provide seamless end-user interaction. Mobile devices can offload their application execution to the cloud servers to improve user experience in terms of faster processing speed, longer battery lifetime and more powerful security services. However, remote cloud servers can incur long delays and poor connectivity over the Internet. Moving cloud servers to the edge of the network reduces the delays while preserving the essential benefits of a high-performance cloud, which is intended to enable a range of latency sensitive mobile applications. Since the edge servers and the mobile devices are rational and thus naturally selfish, they aim to maximize their payoffs with any efforts including launching a range of attacks such as denial-of-service (DOS) attacks [1]–[3].

As an emerging decentralized architecture and distributed computing paradigm, blockchain has recently attracted intensive attention from governments, financial institutions and capital markets due to its decentralization, collective maintenance, programmability and security [4]. Blockchain was first introduced as a decentralized transparent ledger that records transactions across all network nodes without a third-party intermediary [5]. In the blockchain network, each node performing the task of validating and relaying transactions has a copy of the chain with complete information about the transactions that cannot be modified retroactively. Therefore, blockchain can provide insights into network security and data privacy [6]–[8].

This work was supported in part by National Natural Science Foundation of China under Grant 61671396 and CCF-Venustech Hongyan Research Initiative (2016-010).

Game theory has been used to study the defense scheme against attacks in the network [9], [10]. In this paper, we formulate a blockchain security game, in which the mobile device and the edge server are able to launch a range of attacks, and propose a blockchain based punishment scheme to suppress their attack motivation. The Nash equilibria (NEs) of the game are derived and the conditions that each NE exists are provided to disclose how the punishment scheme impacts the attack rates of the mobile device and the edge server.

- We propose a punishment scheme based on the action record on the blockchain to suppress the attack motivation of the edge server and the mobile device, and improve the security performance of the edge network.
- We formulate a blockchain security game and provide the NEs of the game and the conditions under which the NEs exist to disclose how the punishment scheme impacts the adversary behaviors of the device and the server .

The remainder of the paper is organized as follows. We review related work in Section II and present the system model in Section III. We present the blockchain security game and provide the NE of the game in Section IV. Numerical results are provided in Section V and conclusions are offered in Section VI.

II. Related Work

Blockchain has been applied to study data privacy and network security. A personal data management system as designed in [5] uses blockchain as an access-control manager to provide personalized services for mobile users. A blockchain model of cryptography as formulated in [6] protects transactional privacy in the decentralized smart contract system. A cloud-centric IoT system as proposed in [7] uses micro services that can engage other restful services to process requests from edge devices to reduce the network latency, and applies

978-1-5386-4502-4/17/$31.00 ©2017 IEEE

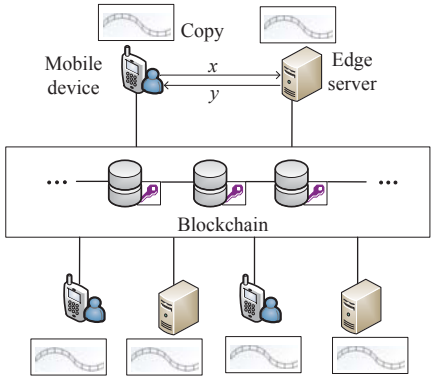


Fig. 1. Illustration of a blockchain based edge network.

blockchain to provide secure and persistent data storage. A blockchain-based smart home framework as formulated in [8] reduces energy consumption and data packet processing overhead of the Internet of Things (IoT) devices. An intelligent transportation system as proposed in [11] utilizes blockchain to provide realtime ride-sharing services for the vehicles.

Game theory has provided insights into network security against attacks. A security game as formulated in [12] investigates the defense scheme against co-resident attacks to maximize the attack cost and minimize the probability of achieving co-residence. An invalid signature identification game as investigated in [13] enables mobile nodes to detect attacks with the optimal delay in wireless mobile networks. A Q-learning based mobile offloading strategy as proposed in [14] reduces the attack rate of the smart attackers in the dynamic offloading game. The two-layer advance persistent threat defense game as formulated in [15] studies the joint threats from an attacker and insiders in the cyber system. A repeated Bayesian game as modeled in [16] changes the configurations of the web applications such as the coding language against attacks.

III. System Model

We consider a blockchain network consisting of M edge servers (S) and N mobile devices (D) that each have a decentralized record on the interactions among them as shown in Fig. 1. A mobile device sends a request to an edge server at time k to obtain real-time service or launches attacks against the server for illegal security gains. We assume the device is able to launch a wide range of attacks at each time, such as DOS attacks, zero-day attack, and password-based attacks. The attacks are split into different categories according to their impacts on the network performance and their attack costs. Without loss of generality, let Level-i attack be more dangerous to the network than Level-j attack, with $i \geq j$. For example, a zero-day attack can be labelled with a higher level than a DOS attack for the higher security risk. The action of the mobile device at time k is denoted by $x \in \{i\}_{0 \leq i \leq L}$. As shown in Table 1, the device sends a service request to the server if $x = 0$, and launches Level-i attack if $1 \leq x \leq L$.

TABLE I

Action Set of the Mobile Device.

Action ID	Physical action
0	Request services
1	Level-1 attack, e.g., fishing
2	Level-2 attack, e.g., password-based attack
...	...
$L-1$	Level-$(L-1)$ attack, e.g., DOS
L	Level-L attack, e.g., zero-day

The server chooses to perform the request from the device or attack it at time k, denoted by $y \in \{j\}_{0 \leq i \leq L}$. Similarly, we assume the server is able to launch a variety of attacks that are split into different levels according to their danger gradations. The server follows the request from the device if $y = 0$, and launches Level-j attack if $1 \leq y \leq L$.

Based on the blockchain network, the system does not require a centralized process or a central unit. Each node in the network checks the actions of others, updates the action records, and shares the new records over the network. The records that are allocated to each node according to its action history determine its probability to receive the network services or node cooperation in the network. The aggressive behaviors recorded on the blockchain are punished by the other nodes in the network to reduce the potential attacker population in the edge network.

IV. Blockchain Security Game

The interaction between an edge server and a mobile device can be formulated as a blockchain security game. As shown in Fig. 1, the mobile device chooses to send a service request to the server or launch attacks against the server, $x \in \mathbf{x} = \{i\}_{0 \leq i \leq L}$. The edge server chooses to follow the request or launch attacks against the device, $y \in \mathbf{y} = \{j\}_{0 \leq j \leq L}$.

Let G_x^y denote the direct benefit of the mobile device choosing x if the edge server takes the action y at time k, which is the gain from the service if $x = y = 0$, the security loss if $y > x = 0$, the illegal gain minus the attack cost if $x > y = 0$, and the illegal gain minus the attack cost and the security loss otherwise. Similarly, the benefit of the server choosing y if the mobile device takes the action x at time k is denoted by C_x^y, which represents the service cost if $x = y = 0$, the sum of the service cost and the security loss if $x > y = 0$, the illegal gain minus the attack cost if $y > x = 0$, and the illegal gain minus the attack cost and the security loss otherwise. The payment to the edge server that follows the request at time k is denoted by $R^{(k)}$. The punishment factor at time k denoted by $\beta^{(k)}$ represents the weight of the action record on the blockchain.

The utility of the mobile device at time k, denoted by $u_D^{(k)}$, depends on the direct gain, the payment to the server, and the

TABLE II

SUMMARY OF SYMBOLS AND NOTATION.

Notation	Definition
$\mathbf{x}/\mathbf{y}$	Action set of the mobile device/edge server
L	Size of the action set of the mobile device/edge server
G_x^y	Direct benefit of the mobile device choosing x if the edge server takes the action y
C_x^y	Direct benefit of the edge server choosing y if the edge server takes the action x
$R^{(k)}$	Payment to the edge server at time k
$\beta^{(k)}$	Punishment factor at time k
$u_D^{(k)}/u_S^{(k)}$	Utility of the mobile device/edge server at time k

punishment for attacks, and is given by

$$u_D^{(k)}(x,y) = G_x^y - \mathrm{I}(x=y=0)R^{(k)} - x\beta^{(k)}. \quad (1)$$

The utility of the server at time k denoted by $u_S^{(k)}$ is given by

$$u_S^{(k)}(x,y) = C_x^y + \mathrm{I}(x=y=0)R^{(k)} - y\beta^{(k)}. \quad (2)$$

The time index k in the superscript is omitted if no confusion occurs. Table 2 summarizes the notation used in the paper.

An NE of the blockchain security game, denoted by (x^*, y^*), consists of the best responses of the mobile device and the edge server if the opponent uses the NE strategy. By definition, we have

$$x^* = \arg\max_{x\in\mathbf{x}} u_D(x, y^*) \quad (3)$$

$$y^* = \arg\max_{y\in\mathbf{y}} u_S(x^*, y). \quad (4)$$

Theorem 1. *The blockchain security game has an NE* $(x^*, y^*) = (0, 0)$*, if*

$$G_0^0 - R \geq \max_{1\leq i\leq L}\left(G_i^0 - i\beta\right) \quad (5)$$

$$C_0^0 + R \geq \max_{1\leq i\leq L}\left(C_0^i - i\beta\right). \quad (6)$$

Proof: By (1), if (5) holds, $\forall\ 1 \leq x \leq L$, we have

$$u_D(0,0) = G_0^0 - R \geq G_x^0 - x\beta = u_D(x,0). \quad (7)$$

Thus, (5) holds for $(x^*, y^*) = (0, 0)$.

Similarly, we have (6) holds for $(x^*, y^*) = (0, 0)$, indicating that $(0, 0)$ is an NE of the game. ■

Theorem 2. *The blockchain security game has an NE* $(x^*, y^*) = (0, j), \forall 1 \leq j \leq L$ *if*

$$G_0^j \geq \max_{1\leq i\leq L}\left(G_i^j - i\beta\right) \quad (8)$$

$$C_0^j - j\beta \geq \max_{1\leq i\leq L}\left(C_0^i - i\beta, C_0^0 + R\right). \quad (9)$$

Proof: The proof is similar to that of Theorem 1. ■

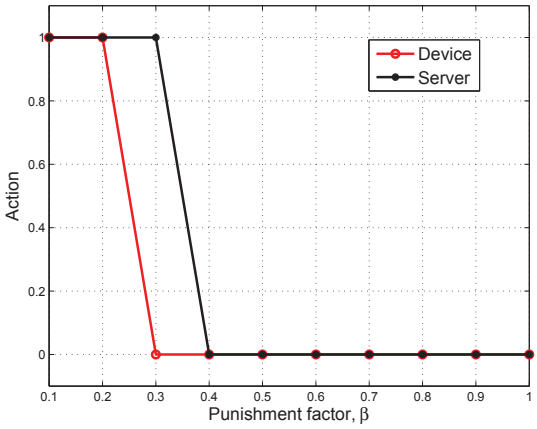
Theorem 3. *The blockchain security game has an NE* $(x^*, y^*) = (i, 0), \forall 1 \leq i \leq L$ *if*

$$G_i^0 - i\beta \geq \max_{1\leq j\leq L}\left(G_j^0 - j\beta, G_0^0 - R\right) \quad (10)$$

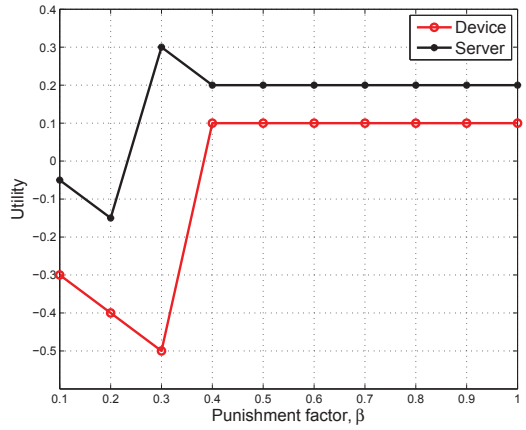
$$C_i^0 \geq \max_{1\leq j\leq L}\left(C_i^j - j\beta\right). \quad (11)$$

Proof: The proof is similar to that of Theorem 1. ■

Theorem 4. *The blockchain security game has an NE*

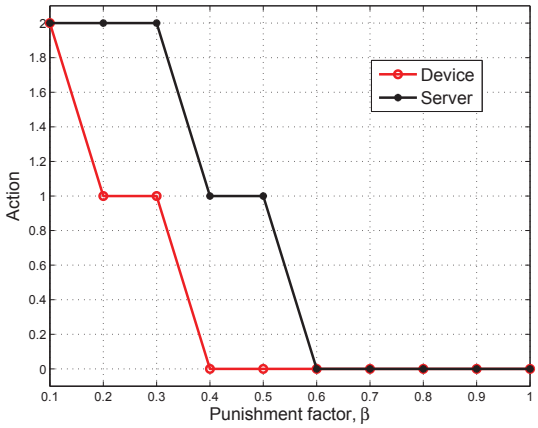


(a) Action

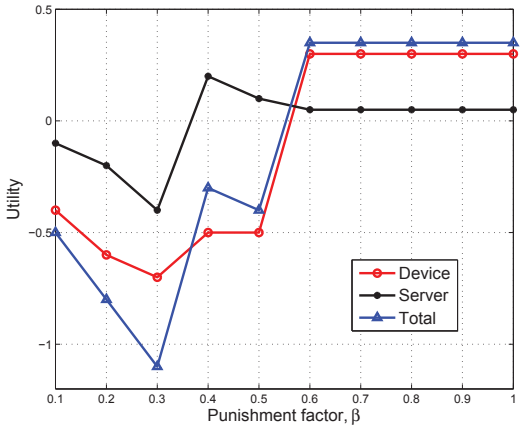


(b) Utility

Fig. 2. Performance of the blockchain security game at the NE, with $R = 0.6$ and $L = 1$.



(a) Action



(b) Utility

Fig. 3. Performance of the blockchain security game at the NE, with $R = 0.6$ and $L = 2$.

$(x^*, y^*) = (i, j), \forall 1 \leq i, j \leq L$ *if*

$$G_i^j - i\beta \geq \max_{1 \leq r \leq L} \left(G_r^j - r\beta, G_0^j \right) \tag{12}$$

$$C_i^j - j\beta \geq \max_{1 \leq r \leq L} \left(C_i^r - r\beta, C_i^0 \right). \tag{13}$$

Proof: The proof is similar to that of Theorem 1. ■

V. Numerical Results

Numerical results illustrating Theorems 1 through 4 are provided to illustrate the performance of the blockchain security game, with $R = 0.6$ and $L = 1$. As shown in Fig. 3, both the mobile device and the edge server tend to behave nicely as punishment factor increases, because the attack motivations of the device and the server are suppressed as the weight of the action record changes at 0.3 and 0.4, respectively. The turning points of the punishment factor $\beta = 0.3$ and 0.4 are given by Eqs. (5)-(6), (8)-(9) and (12)-(13). In this case, the utility of the device decreases by 66.3% as β increases from 0.1 to 0.3 because of the increasing punishment weight and security loss, and increases from -0.5 to 0.1 as β changes at 0.3. That is because the server chooses to follow the service request to avoid punishment.

As shown in Fig. 3, the device and the edge server launch Level-2 attack against each other if the punishment factor is small and tend to behave nicely if the network takes into account the attack behavior with more weights in the action record on the blockchain. The total utility of the device and the server decreases with the punishment factor and increases if they take friendly behaviours. For example, the total utility decreases from -0.5 to -1.2 as β increases from 0.1 to 0.3, and increases to -0.3 as β changes at 0.3. The reason is that the increasing punishment factor prevents adversary behaviors of the server and the device.

VI. Conclusion

In this work, we have formulated a blockchain security game to investigate a punishment scheme based on the action record on the blockchain. The NEs of the security game and the conditions under which the equilibria exist have been provided, showing that a mobile device and a edge server tend to behave nicely if the punishment weight is large. A Q-learning based security scheme has been proposed for the dynamic game to improve the network security performance, e.g., the attack rate of the server decreases by 66.7% compared with the benchmark strategy.

References

[1] H. Zhang, P. Cheng, L. Shi, and J. Chen, "Optimal denial-of-service attack scheduling with energy constraint," *IEEE Trans. Automatic Control*, vol. 60, no. 11, pp. 3023 – 3028, Nov. 2015.

[2] X. Du, Y. Xiao, M. Guizani, and H. H. Chen, "An effective key management scheme for heterogeneous sensor networks," *Ad Hoc Networks, Elsevier*, vol. 5, no. 1, pp. 24–34, Jan. 2007.

[3] X. Du, M. Guizani, Y. Xiao, and H. H. Chen, "A routing-driven elliptic curve cryptography based key management scheme for heterogeneous sensor networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1223–1229, Mar. 2009.

[4] M. Swan, "Blockchain: Blueprint for a new economy," *O'Reilly Media, Inc.*, Feb. 2015.

[5] G. Zyskind and O. Nathan, "Decentralizing privacy: Using blockchain to protect personal data," in *Proc. IEEE Security and Privacy (SP)*, pp. 180–184, San Jose, CA, May 2015.

[6] A. Kosba, A. Miller, E. Shi, Z. Wen, and C. Papamanthou, "Hawk: The blockchain model of cryptography and privacy-preserving smart contracts," *Proc. IEEE Symposium Security and Privacy*, pp. 839–858, San Jose, CA, May 2015.

[7] M. Samaniego and R. Deters, "Hosting virtual iot resources on edge-hosts with blockchain," in *Proc. IEEE Int. Conf. Computer and Information Technology (CIT)*, pp. 180–184, Nadi, Fiji, Dec. 2016.

[8] A. Dorri, S. S. Kanhere, R. Jurdak, and P. Gauravaram, "Blockchain for iot security and privacy: The case study of a smart home," *Pro. IEEE Int. Conf. Pervasive Computing and Communications Workshops*, pp. 618–623, Kona, Big Island, HI, Mar. 2017.

[9] L. Xiao, D. Xu, C. Xie, N. B. Mandayam, and H. V. Poor, "Cloud storage defense against advanced persistent threats: A prospect theoretic study," *IEEE J. Selected Areas Commun.*, vol. 35, no. 3, Mar. 2017.

[10] A. Garnaev, M. Baykal-Gursoy, and H. V. Poor, "Security games with unknown adversarial strategies," *IEEE Trans. Cybernetics*, vol. 46.

[11] Y. Yuan and F. Wang, "Towards blockchain-based intelligent transportation systems," in *Proc. IEEE Int. Conf. Intelligent Transportation Systems (ITSC)*, pp. 2663–2668, Rio de Janeiro, Brazil, Dec. 2016.

[12] Y. Han, T. Alpcan, J. Chan, C. Leckie, and B. I. Rubinstein, "A game theoretical approach to defend against co-resident attacks in cloud computing: Preventing co-residence using semi-supervised learning," *IEEE Trans. Information Forensics and Security*, vol. 11, no. 3, pp. 556–570, Mar. 2016.

[13] J. Chen, Q. Yuan, G. Xue, and R. Du, "Game-theory-based batch identification of invalid signatures in wireless mobile networks," in *Proc. IEEE Conf. Comput. Commun. (INFOCOM)*, pp. 262–270, HK, May 2015.

[14] L. Xiao, C. Xie, T. Chen, H. Dai, and H. V. Poor, "A mobile offloading game against smart attacks," *IEEE Access*, vol. 4, pp. 2281–2291, May 2016.

[15] P. Hu, H. Li, H. Fu, D. Cansever, and P. Mohapatra, "Dynamic defense strategy against advanced persistent threat with insiders," in *Proc. IEEE Conf. Comput. Commun. (INFOCOM)*, pp. 747–755, HK, May 2015.

[16] S. Sengupta, S. G. Wang, et al., "A game theoretic approach to strategy generation for moving target defense in web applications," in *Proc. ACM Conf. Autonomous Agents and Multiagent Systems*, pp. 178–186, São Paulo, Brazil, May 2017.