Optimal Block Propagation and Incentive Mechanism for Blockchain Networks in 6G

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***Abstract*—Due to the prominent advantages of decentralization, transparency, security, and traceability, blockchain technologies have attracted ever-increasing attention from academia and industry, which can be applied to establish secure and reliable resource sharing platforms for future networks and applications. Especially, with the promising 6G technology which has large bandwidth and space-air-ground integrated coverage, blockchains have been evolved into 6G-enabled blockchain and envisioned to build various decentralized data and resource management systems. However, for 6G-enabled wireless blockchain networks, there still exist many challenges for their development and prosperity, e.g., large block propagation delay and propagation incentive. Therefore, this paper focuses on addressing the block propagation challenges. Firstly, inspired by epidemic models, we classify consensus nodes into five different states and establish a block propagation model for public blockchains that depicts block propagation laws. Then, considering consensus nodes are limited rational, we propose an Incentive Mechanism based on evolutionary game for Block Propagation (marked as BPIM) to minimize the block propagation delay. Numerical results demonstrate that compared with traditional routing algorithms, BPIM has better block propagation efficiency and greater incentive strength.**

***Index Terms*—Blockchain, 6G, block propagation, incentive mechanism, routing.**

I. Introduction

Relying on encryption technologies and consensus algorithms of distributed systems, blockchain as a distributed ledger technology can effectively solve the problem of the single point of failure and security vulnerabilities caused by centralized nodes. Since blockchains can achieve cross-domain trust in a highly distributed system without a trusted center, they have attracted widespread attention from all walks of life after their birth, such as smart cities [1], smart healthcare [2], smart grid [3], and Internet of vehicles [4]–[6]. Therefore, blockchains are regarded as indispensable technologies for building trust in future applications and emerging scenarios.

Recently, the promising 6G technology has attracted increasing attention. In contrast with the infrastructure requirements of 5G, 6G is a fully connected network integrating terrestrial and satellite wireless communications for large-scale coverage, ultra-reliable, and low latency communications [7]–[9], which enhances the connectivity and flexibility of 5G. As an integrated space-ground information system, 6G enables exciting new applications and unprecedented technological trends, such as multi-sensory XR applications, metaverse [10], wireless brain-computer interaction, and Distributed Ledger Technology (DLT). For blockchain technologies, 6G can greatly increase the coverage and bandwidth of blockchain systems and allow more miners to join public blockchains, which effectively improves blockchain scalability and achieves higher-level security and better decentralization.

Although 6G brings attractive benefits to blockchain networks [11] [12], the 6G-enabled wireless blockchain networks have the characteristics of large coverage and high heterogeneity, which affects blockchain performance to a certain extent. Besides, the frequent mobility of miners changes the topology of wireless blockchains, which increases the uncertainty of information transmission, thus further increasing block propagation delay. Especially, in public blockchains, new blocks need to be broadcasted to most miners (or even all miners) in the entire miner network for verification, thus causing long propagation time. When block propagation delay is too large, there may be an excessive number of forks (competitive consensus) [13] or insufficient signatures collection (collaborative consensus), resulting in the blockchain system malfunction. In addition, too large propagation delay may significantly prolong the generation interval of blocks. Hence, to effectively improve the 6G-enabled wireless blockchain network throughput, block propagation optimization is particularly significant. So far, a few studies have reduced block propagation delay by optimizing blockchain network topology [14] [15] and block verification delay [13] [16], but without considering block propagation routing optimization.

Moreover, most of existing studies simply assume that miners cooperate to share their resources during service provision without considering the miners' rationality. Actually, there may be competition for resource benefits among smart devices (i.e., miners) in the 6G-enabled wireless blockchain network. So when studying block propagation optimization

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for 6G-enable wireless blockchain networks, it is necessary to establish an efficient incentive mechanism to promote miners to propagate blocks actively and reduce block propagation delay efficiently [17] [18].

Motivated by the above observations, this paper aims to establish a theoretical model of block propagation for public blockchains without changing the network topology and find out factors that affect the performance of blockchain to achieve block propagation optimization under the security requirements. The main contributions of this paper are summarized as follows:

- We classify consensus nodes into five different states by analyzing the block propagation process and inventively establish a block propagation model for public blockchains inspired by epidemic models.
- From the perspectives of block verification and block propagation, we establish an incentive mechanism based on evolutionary game for block propagation considering the rationality of miners and analyze the behavior of miners based on evolutionary game.
- We conduct extensive simulations on the block propagation model and the incentive mechanism to verify the efficiency improvement of block propagation.

The remainder of this paper is organized as follows. Section II introduces the block propagation model for public blockchains and the incentive mechanism based on evolutionary game for block propagation to achieve block propagation optimization. Section III conducts experimental simulations of the two models to reveal the underlying laws of block propagation. Section IV concludes the whole paper.

II. System Model

In the 6G-enabled wireless blockchain network, mobile users at the physical layer are connected in a P2P manner. The transactions between them will be packaged into blocks, and the blocks are propagated in the miner network in the form of *rumor mongering* [19]. To be specific, when a miner completes the verification of a new block, it randomly selects k adjacent miners and forwards the new block to them. When the miners receive the block, they will first verify the block. If the verification is successful, they will also randomly select k adjacent miners for propagation, otherwise, the block will be discarded. Finally, whether the block can be successfully added to the blockchain depends on the verification results of all miners. To better study the block propagation process, the mobile users of the physical layer are treated as miner nodes at the network layer, as shown in Fig. 1.

A. Block Propagation Model for Public Blockchains

Since the block propagation process is similar to the spread of infectious diseases, inspired by epidemic models [20], a block propagation model for public blockchains is constructed. By analyzing the block propagation mechanism in the public blockchain, consensus nodes (i.e., miner nodes) can be classified into five different states: ignorants, spreaders, unspreaders, refusers, and evildoers.

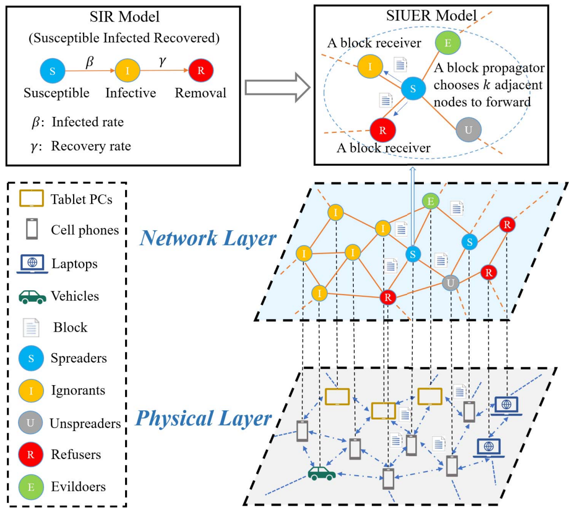

Fig. 1: 6G-enabled wireless blockchain block propagation model.

More specifically, ignorants are initial nodes that have not received the block. Spreaders mean that nodes have received the block and verified the block is successful, and the block will be forwarded to k adjacent nodes. Unspreaders mean that nodes have received the block but failed to verify the block, and they will refuse to forward the block to adjacent nodes, which can avoid wasting network resources. Refusers are immune nodes, which means that nodes have received the block, and when the block is received again, the block is not forwarded but discarded. Spreaders and unspreaders become refusers with a probability of $\frac{1}{k}$ [21]. Evildoers are malicious nodes, which means that destroy the benefits of most nodes in the system, such as directly forwarding unverified blocks, *Sybil Attack*, etc. When each round of interaction starts, ignorants will misbehave with a certain probability. When each round of interaction ends, evildoers will return to being normal with a certain probability. According to [20], a state transition diagram of the block propagation model is shown in Fig. 2.

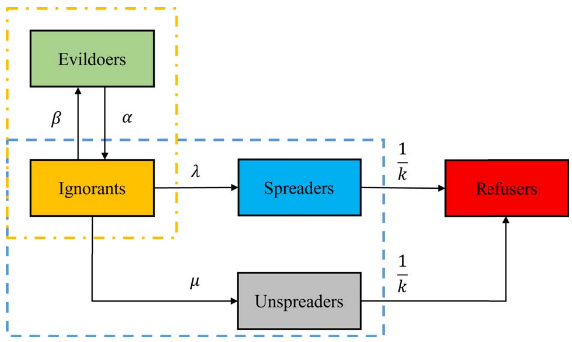

Fig. 2: A state transition diagram of SIUER model.

Considering that a network has N nodes, it can be regarded as an undirected graph $G(V, E)$, where V is the set of vertices and E is the set of edges. As shown in Fig. 2, there is a conversion relationship between nodes. The specific conversion rules are described as follows:

- When ignorants receive a block forwarded from spreaders, ignorants will verify the block. If the verification is successful, ignorants will be converted to spreaders with probability λ. Otherwise, ignorants will be converted to unspreaders with probability μ, where λ is forwarding probability, μ is non-forwarding probability, and the sum of λ and μ is 1.
- When each round of interaction starts, ignorants will be converted to evildoers with probability β. When each round of interaction ends, evildoers will be converted to ignorants with probability α, where β is evil probability, and α is recovery probability.
- When spreaders and unspreaders receive the block again, or after each interaction, spreaders and unspreaders are converted to refusers with probability $\frac{1}{k}$, where $\frac{1}{k}$ is immunity probability.

Suppose $i(t)$, $s(t)$, $u(t)$, $r(t)$, and $e(t)$ represent the proportion of ignorants, spreaders, unspreaders, refusers, and evildoers at time t, respectively. They satisfy the following condition: [20]

$$i(t)+s(t)+u(t)+r(t)+e(t)=1. \tag{1}$$

According to Fig. 2, the variation of $i(t)$ at Δt can be obtained as follows:

$$\begin{aligned} N[i(t+\Delta t)-i(t)] &= \alpha Ne(t)\Delta t-\beta Ni(t)\Delta t \\ &\quad - k\lambda(1-\beta)Ns(t)i(t)\Delta t \\ &\quad - k\mu(1-\beta)Ns(t)i(t)\Delta t. \end{aligned} \tag{2}$$

$\Longleftrightarrow$

$$\begin{aligned} \frac{i(t+\Delta t)-i(t)}{\Delta t} &= \alpha e(t)-\beta i(t)-k\lambda(1-\beta)s(t)i(t) \\ &\quad - k\mu(1-\beta)s(t)i(t). \end{aligned} \tag{3}$$

Take the limit of $\Delta t\to 0$ on both sides at the same time, we can get

$$\begin{aligned} \frac{di(t)}{dt} &= \alpha e(t)-\beta i(t)-k\lambda(1-\beta)s(t)i(t) \\ &\quad - k\mu(1-\beta)s(t)i(t). \end{aligned} \tag{4}$$

The other differential equations can be calculated by the above process. So the differential equation system of the block propagation model for public blockchains can be obtained:

$$\begin{cases} \frac{di(t)}{dt}=\alpha e(t)-\beta i(t)-k(\lambda+\mu)(1-\beta)s(t)i(t) \\ \frac{ds(t)}{dt}=k\lambda(1-\beta)s(t)i(t)-\frac{1}{k}(1+s(t))s(t) \\ \frac{du(t)}{dt}=k\mu(1-\beta)s(t)i(t)-\frac{1}{k}(1+s(t))u(t) \\ \frac{dr(t)}{dt}=\frac{1}{k}(1+s(t))s(t)+\frac{1}{k}(1+s(t))u(t) \\ \frac{de(t)}{dt}=\beta i(t)-\alpha e(t). \end{cases} \tag{5}$$

k means that a node selects k adjacent nodes to forward the block, and the initial value of each proportion is:

$$i(t)=\frac{N-1}{N}, s(t)=\frac{1}{N}, u(t)=0, r(t)=0, e(t)=0. \tag{6}$$

B. Incentive Mechanism Based on Evolutionary Game for Block Propagation

For the reason that the 6G-enabled wireless blockchain networks have the characteristics of large coverage and high heterogeneity, miners are difficult to choose the best strategy in a complex environment for maximizing their benefits, and the behavior of miners is limited rational, so miners often make relatively satisfactory decisions based on the local information they have. Evolutionary game theory can help miners only consider the limited benefits in the block propagation process, and the behavior of miners will evolve to the final stable state in the process of continuous trials and errors, which is called evolutionary stable strategy [22]. Based on the evolutionary stable strategy, we can better formulate reasonable optimization strategies and make blocks propagate rapidly and steadily to the miner network.

Therefore, we propose an Incentive Mechanism based on evolutionary game for Block Propagation (marked as BPIM). We study the changes in forwarding probability under the action of the incentive mechanism and find the optimal strategy combination, which can optimize the block propagation mechanism and better achieve the overall network consensus.

Considering all the miners are limited rational, block propagation decisions simultaneously move in a game where one party takes an action without knowing the strategy the other party is taking, that is, when deciding on their actions, it is inferred that other parties will also act rationally.

1) Payoff matrix of evolutionary game: The consensus nodes essentially can be divided into two groups, namely block propagators (i.e., spreaders) and block receivers (i.e., nodes other than spreaders), and the characteristics of these two groups are consistent.

We define that Q is block verification cost, and P is block verification reward. Since block verification is performed before block propagation, it is assumed that P is greater than Q for the convenience of research. Besides, we define that M is block propagation cost, and I is block propagation reward. If and only if block receivers propagate the block, both block propagators and block receivers can receive the block propagation reward.

In this subsection, an evolutionary game matrix will be established for the participants of block propagation. The miners' action strategies are whether to propagate the block, and their revenue functions are the actual benefit of block verification plus the actual benefit of block propagation. The following four cases of the evolutionary game will be analyzed.

- When block propagators forward the block, and block receivers also forward the block, both block propagators and block receivers will receive the block propagation reward, in which block propagators' revenue functions are $(P-Q+I-M)$, and block receivers' revenue functions also are $(P-Q+I-M)$.
- When block propagators forward the block, but block receivers do not forward the block, block propagators will not get the block propagation reward even propagating the

TABLE I: the Benefit Matrix of Block Propagators and Block Receivers in Public Blockchains.

Receiver strategy / Propagator strategy	Forwarding probability y	Non-forwarding probability $(1-y)$
Forwarding probability x	$(P-Q+I-M, P-Q+I-M)$	$(P-Q-M, P-Q)$
Non-forwarding probability $(1-x)$	$-$	$(P-Q, 0)$

block, in which their revenue functions are $(P-Q-M)$, and block receivers' revenue functions are $(P-Q)$.

- When block propagators do not forward the block, but block receivers forward the block, the logic does not hold, so this situation does not exist.
- When block propagators do not forward the block, and block receivers do not forward the block, block propagators' revenue functions are $(P-Q)$, and block receivers' revenue functions are 0.

Assume that the forwarding probability of block propagators is x, and the non-forwarding probability is $(1-x)$. The forwarding probability of block receivers is y, and the non-forwarding probability is $(1-y)$, where x, y is consistent with λ described above. According to the analysis of the evolutionary game, the benefit matrix between block propagators and block receivers in public blockchains can be obtained, as shown in Table I.

2) Revenue function of block participants: Assume that the expected revenues of block propagators forwarding the block and non-forwarding the block are G_{1Y} and G_{1N}, respectively, and the group average revenue is G_1, then:

$$\begin{aligned} G_{1Y} &= y(P-Q+I-M) + (1-y)(P-Q-M) \\ &= yI + P - Q - M. \end{aligned} \tag{7}$$

$$G_{1N} = (1-y)(P-Q). \tag{8}$$

$$\begin{aligned} G_1 &= xG_{1Y} + (1-x)G_{1N} \\ &= xyI + x(P-Q-M) + (1-x)(1-y)(P-Q). \end{aligned} \tag{9}$$

Similarly, the expected revenues of block receivers forwarding the block and non-forwarding the block are G_{2Y} and G_{2N}, respectively, and the group average revenue is G_2, then:

$$G_{2Y} = x(P-Q-M). \tag{10}$$

$$G_{2N} = x(P-Q). \tag{11}$$

$$G_2 = xy(P-Q-M) + x(1-y)(P-Q). \tag{12}$$

3) Replication dynamic equation for forwarding probability: The replication dynamic equation for forwarding probability of block propagators is:

$$H(x) = \frac{dx}{dt} = x(G_{1Y} - G_1) = x(1-x)[y(I+P-Q) - M]. \tag{13}$$

- If $y = \frac{M}{I+P-Q}$, then $H(x) \equiv 0$, and all levels are stable.
- If $y \neq \frac{M}{I+P-Q}$, let $H(x) = 0$, then $x = 0$ and $x = 1$ are the two stable values of x, and the derivative of $H(x)$ with respect of x can be obtained:

$$\frac{dH(x)}{dx} = (1-2x)[y(I+P-Q) - M]. \tag{14}$$

Due to the requirement of evolutionary stable strategy $\frac{dH(x)}{dx} < 0$, comparing the relationship between y and $\frac{M}{I+P-Q}$, the following insights can be obtained:

Insight 1. When $y > \frac{M}{I+P-Q}$, then $\frac{dH(x)}{dx} < 0$, and $x = 1$ is the equilibrium point. When $I \gg \frac{P-Q+M}{2}$ or $M \ll (I+P-Q)$, then $\frac{M}{I+P-Q} \approx 0$, and $y > \frac{M}{I+P-Q}$ is always established.

Insight 2. When $y < \frac{M}{I+P-Q}$, then $\frac{dH(x)}{dx} < 0$, and $x = 0$ is the equilibrium point. When $(I+P-Q) < M$, then $\frac{M}{I+P-Q} > 1$, and $y < \frac{M}{I+P-Q}$ is always established.

Similarly, the replication dynamic equation for forwarding probability of block receivers is:

$$H(y) = \frac{dy}{dt} = y(G_{2Y} - G_2) = xy(y-1)(M-I). \tag{15}$$

- If $M = I$ or $x = 0$, then $H(x) \equiv 0$, and all levels are stable.
- If $M \neq I$ and $x \neq 0$, let $H(y) = 0$, then $y = 0$ and $y = 1$ are the two stable values of y, and the derivation of $H(y)$ with respect to y can be obtained:

$$\frac{dH(y)}{dy} = x(M-I)(2y-1). \tag{16}$$

Since $x > 0$, the following insights can be obtained:

Insight 3. When $M < I$, then $\frac{dH(y)}{dy} < 0$, and $y = 1$ is the equilibrium point.

Insight 4. When $M > I$, then $\frac{dH(y)}{dy} < 0$, and $y = 0$ is the equilibrium point.

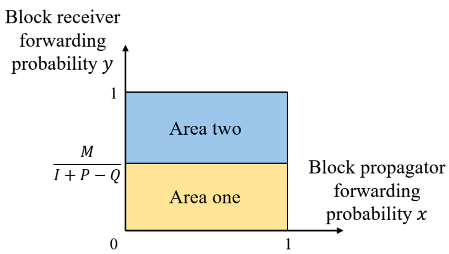

Fig. 3: A diagram of evolutionary game coordinates of miners.

4) Game equilibrium analysis: Based on the above game solutions, the following equilibrium states can be obtained, as shown in Fig. 3.

- When the initial state falls in area two, if $(I+P-Q) > 0$ and $M < I$, the final game result between block propagators and block receivers is (forwarding, forwarding).
- When the initial state falls in area two, if $(I+P-Q) > 0$ and $M > I$, the game result of block propagators and block receivers at the beginning is (forwarding, non-forwarding). However, since block receivers do not forward the block, block propagators have to bear the block propagation cost but cannot obtain the block propagation reward, so the game result between block propagators and

block receivers gradually evolves into (non-forwarding, non-forwarding).

- When the initial state falls in area one, if $(I+P-Q)>0$ and $M>I$, then $x=0$ and $y=0$, and the final game result between block propagators and block receivers is (non-forwarding, non-forwarding).

To sum up, when the game result of miners is in the first equilibrium state, the block can be better propagated among the miners. Therefore, the whole network verification can be completed faster and the consensus of the whole network can be reached more quickly.

III. Performance Evaluation

A. Simulation Setting

To provide a theoretical basis for improving the efficiency of block propagation, we evaluate BPIM performance and analyze block propagation laws in this section. First, compare BPIM performance with traditional routing algorithms that do not consider incentive mechanisms. Second, study the influence of some significant parameters on block propagation and summarize the propagation laws. The key parameter configuration is shown in Table II [20].

TABLE II: Key Parameters in the Simulation.

Parameters	Value
Total number of nodes N	4000
Adjacent node selection number k	2∼4
Forwarding probability λ	0.2∼1
Non-forwarding probability μ	0∼0.8
Evil probability β	0.2∼1
Recovery probability α	0.3
Block propagation reward I	0∼1
Block propagation cost M	0∼1
Block verification reward P	0∼1
Block verification cost Q	0∼1

We compare the proposed BPIM with following two other routing algorithms as follows.

- *Greedy Routing*. Block propagators only consider their current best benefits of themselves but do not consider the impact of their own propagation behavior on the block propagation in the miner network.
- *Random Routing*. Block propagators do not consider the role of the incentive mechanism and randomly select adjacent nodes to propagate the block.

B. Result Discussion

Fig. 4 shows the forwarding probability of BPIM, random routing, and greedy routing during block broadcast. As each round of interaction continues, the forwarding probability corresponding to each routing algorithm increases. Besides greedy routing that performs best as expected, BPIM is always ahead of random walk in forwarding probability. Moreover, the greater the incentive strength, the greater the growth rate of the forwarding probability of BPIM. For example, the green line (i.e., incentive strength $I/M=2$) means that it takes about 35 epochs for the forwarding probability to reach the maximum value, while the blue line (i.e., incentive strength $I/M=4$) shows that it only takes about 15 epochs for the forwarding probability to reach the maximum value.

Fig. 5 illustrates how the density of refusers changes over time for different forwarding probability λ. We can find that as time grows up, the density of refusers corresponding to different λ increases. The larger λ, the faster the number of refusers grows, and the larger the number of refusers in the end, which indicates that the higher the forwarding probability, the more consensus nodes will complete the verification and reach a consensus faster. Therefore, the performance of BPIM is better than that of random routing. The reason is that under the action of the incentive mechanism, block propagators will consider their benefits to select appropriate adjacent nodes instead of randomly selecting adjacent nodes to propagate blocks, which is not only conducive to improving the efficiency of block propagation but also avoids the problem of block retransmission. However, greedy routing only considers the local optimality of propagation, which is bound to greatly increase the redundancy of blocks in the network. To sum up, the overall performance of BPIM is better than that of random routing and greedy routing.

Fig. 6 shows how the density of evildoers changes over time for different k. We can see that no matter what the value of k is, the number of evildoers increases first and then decreases. It shows that in the beginning, most ignorants want to gain greater benefits by doing evil. However, with the gradual expansion of the consensus scale, the cost of doing evil increases, resulting in a decrease in the number of evildoers. Besides, the larger k, the smaller the number of evildoers, the reason is that due to the increase in the number of nodes participating in the consensus, the degree of decentralization of the network is enhanced, resulting in the cost of doing evil increases, thus reducing the number of evildoers.

Fig. 7 illustrates how the density of spreaders changes over time for different evil probability β. We can see that the smaller β, the larger the number of spreaders, and when β exceeds a certain threshold, there are no more spreaders in the network. The reason is that reducing the number of evildoers will help more ignorants turn into spreaders, therefore, blockchain systems can use a reasonable punishment mechanism that increases the cost of doing evil to reduce the evil probability, thereby increasing the number of block propagators and speeding up the efficiency of block propagation.

IV. Conclusion

In this paper, we have analyzed the block propagation mechanism in the 6G-enabled wireless blockchain network. Inspired by epidemic models, we have classified the consensus nodes of the network into five different states and established a block propagation model for public blockchains to reveal block propagation laws. Then, we have proposed an incentive mechanism based on evolutionary game for block propagation after analyzing the behavior of limited rational miners. Finally, numerical results have demonstrated that the proposed mechanism can accelerate block propagation and reach a consensus

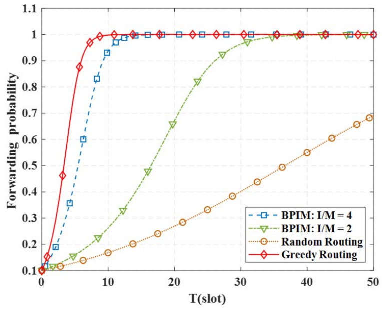

Fig. 4: Forwarding probability for different routing algorithms in period T during block broadcast.

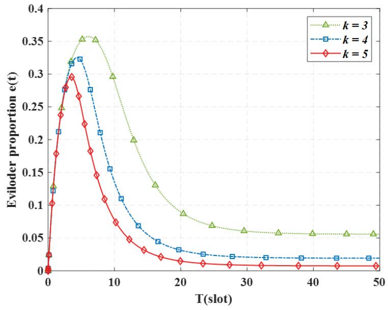

Fig. 6: Density of evildoers under different k with $\lambda = 0.7$, $\alpha = 0.3$, $\beta = 0.2$.

faster, and the greater the incentive strength, the higher the consensus efficiency.

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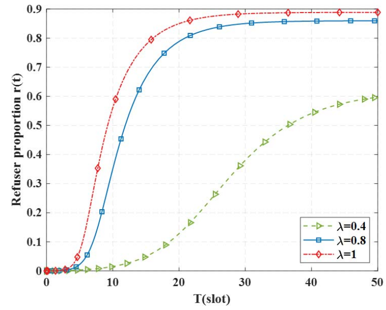

Fig. 5: Density of refusers under different forwarding probability λ with $k = 3$, $\alpha = 0.3$, $\beta = 0.2$.

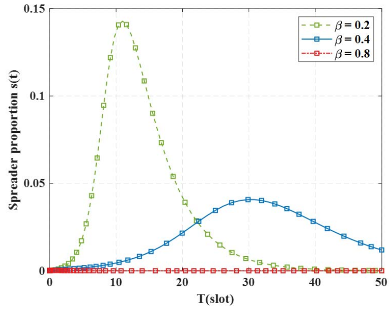

Fig. 7: Density of spreaders under different evil probability β with $k = 3$, $\lambda = 0.7$, $\alpha = 0.3$.

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