Extortion provides alternative routes to the evolution of cooperation in structured populations

Xiongrui Xu,[1] Zhihai Rong,[1,2,3,*] Zhi-Xi Wu,[4,†] Tao Zhou,[2] and Chi Kong Tse[3]

[1]*CompleX Lab, Web Sciences Center, University of Electronic Science and Technology of China, Chengdu 611731, China*
[2]*Big Data Research Center, University of Electronic Science and Technology of China, Chengdu 611731, China*
[3]*Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong*
[4]*Institute of Computational Physics and Complex Systems, Lanzhou University, Lanzhou, Gansu 730000, People's Republic of China*

(Received 19 September 2016; revised manuscript received 2 April 2017; published 1 May 2017)

In this paper, we study the evolution of cooperation in structured populations (individuals are located on either a regular lattice or a scale-free network) in the context of repeated games by involving three types of strategies, namely, unconditional cooperation, unconditional defection, and extortion. The strategy updating of the players is ruled by the replicator-like dynamics. We find that extortion strategies can act as catalysts to promote the emergence of cooperation in structured populations via different mechanisms. Specifically, on regular lattice, extortioners behave as both a shield, which can enwrap cooperators inside and keep them away from defectors, and a spear, which can defeat those surrounding defectors with the help of the neighboring cooperators. Particularly, the enhancement of cooperation displays a resonance-like behavior, suggesting the existence of optimal extortion strength mostly favoring the evolution of cooperation, which is in good agreement with the predictions from the generalized mean-field approximation theory. On scale-free network, the hubs, who are likely occupied by extortioners or defectors at the very beginning, are then prone to be conquered by cooperators on small-degree nodes as time elapses, thus establishing a bottom-up mechanism for the emergence and maintenance of cooperation.

DOI: 10.1103/PhysRevE.95.052302

I. INTRODUCTION

Cooperation plays a key role in both nature and society, from cellular organisms to international affairs. Yet, the emergence of cooperation under the assumption of individual's selfishness remains a riddle, which has attracted the attention of scientists from various fields who employ evolutionary game theory as a theoretical framework [1–5]. The Prisoner's Dilemma (PD) is a game model that receives the most attention as a metaphor of cooperation between unrelated individuals [6], in which two players interact simultaneously with each other by choosing either cooperation or defection as a strategy. They both receive a reward R for mutual cooperation and a punishment P for mutual defection. A cooperator's payoff is S when her opponent adopts defection, receiving T as the temptation to defect. The parameters satisfy $T > R > P > S$ and $2R > T + S$, so that it is always better to defect regardless of the opponent's behavior, resulting in an outcome of mutual defection, although mutual cooperation yields the highest collective payoff.

To understand the ubiquitous existence of cooperative phenomena in nature, several celebrated mechanisms have been revealed, including kin selection, direct reciprocity, indirect reciprocity, network reciprocity, and multilevel selection [7,8]. Previous researches on the PD game showed that population structure can help cooperators to form tight clusters to survive on various regular lattices [4,9,10], regular random graphs [11–13], and even dominate on scale-free networks [14–17]. There are also many other factors playing important roles in the evolution of cooperation [18–20], such as noise [9,10,13], heterogeneous teaching activity [21–24], preferential selection [25–27], separation of time scales [28–30], and aspiration level [31,32].

Recently, Press and Dyson discovered a class of strategies called zero-determinant (ZD) strategies, which allows the focal player to enforce a linear relation between her own payoff and the opponent's payoff unilaterally in the repeated PD games [33]. Particularly, a subset of ZD strategies, called extortion strategies, attracted a lot of attention. Extortion strategies ensure that the extortioner X can receive a payoff surplus exceeding the surplus of her co-player Y by a fixed percentage, presented as $(P_X - P) = \chi(P_Y - P)$, where P_X and P_Y are the long-term payoffs of X and Y, and $\chi > 1$ is the extortion factor characterizing the strength of extortion. This feature implies that extortion strategies may dominate any evolutionary opponents [33]. Yet, if an extortioner meets another extortioner or a defector, both of them will get nothing, which implies that extortion strategies are evolutionarily unstable in a well-mixed population [34]. Hilbe *et al.* found that although extortion strategies are evolutionarily unstable in a large well-mixed population, they may serve as catalysts to promote the emergence of cooperation [35]. Recent investigations showed that extortion strategies can help cooperators to persist stably in structured populations when the strategy updating is driven by myopic response dynamics or aspiration-driven dynamics [36–41].

We noticed that in previous literature, the strategy updating rules of the players are mostly motivated by social dynamics, such as imitation and self-inference [34–40]. It is still unclear how extortion strategies affect the evolution of cooperation in structured populations whenever the system is driven by a biologically inspired rule, for instance, the replicator dynamics [14–16,42,43]. In this paper, we intend to address this issue by studying the evolutionary PD games with three strategies, say unconditional cooperation (C), unconditional defection (D), and extortion (E_χ) on the square lattice as well

*rongzhh@gmail.com
†eric0724@gmail.com

as on the scale-free networks, where the strategy updating is governed by the finite population analog of replicator-like dynamics [14–16,42,43]. Interestingly, we find that the evolution of cooperation can be established via two different routes, depending on whether the underlying interaction is a homogeneous lattice or a heterogeneous network. Our work reveals a nontrivial role of the population structure and the microscopic strategy dynamics in the evolution of cooperation.

II. METHODS AND MODELS

In this study, we adopt one of the classical iterated prisoner's dilemma game models, called "donation game" [2], and consider the competition among C, D, and E_χ strategies on either a square lattice of size $L \times L$ with periodic boundary conditions or on the Barabási-Albert (BA) scale-free networks [44]. A cooperator pays a cost c to provide a benefit b for her opponent, and a defector reaps without sowing, resulting in the parameters $T = b$, $R = b - c$, $S = -c$, and $P = 0$. With the introduction of extortioners (with the extortion factor χ), the long-term payoff matrix involving C, D, and E_χ can be formulated as [35,37]

	C	D	E_χ
C	$b-c$	$-c$	$\frac{b^2-c^2}{b\chi+c}$
D	b	0	0
E_χ	$\frac{(b^2-c^2)\chi}{b\chi+c}$	0	0

(1)

Since $b > c$ and $\chi > 1$, it is easy to find that here exists a snowdrift-like relationship between an extortioner and a cooperator, i.e., the best response depends on the opponent: to cooperate if the other extorts, but to extort if the other cooperates. When an extortioner meets a defector, both of them get nothing, and the relationship between them is neutral. For simplicity, we set $b - c = 1$ so that only two free parameters are left in our model, the benefit factor b and the extortion factor χ.

The competition among different strategies is carried out by implementing the finite population analog of replicator-like dynamics [5,14]. In each round, after playing games with all connected neighbors, an individual x acquires her accumulated payoff P_x with her current strategy S_x in terms of the payoff matrix Eq. (1). Then her strategy S_x is replaced by the strategy of one randomly chosen neighbor, say y (with strategy S_y), with the probability

$$W(S_x \leftarrow S_y) = \frac{P_y - P_x}{\max(k_x,k_y)H}, \quad (2)$$

where k_x (k_y) represents the degree of x (y), and H is the maximal possible difference between the payoffs of two players in each encounter. Since for all $\chi > 1$, $\frac{(b^2-c^2)\chi}{b\chi+c} < b$, here we set $H = b + c$.

Initially, all three strategies, C, D, and E_χ, are distributed with equal probability in the population. Then, by varying the value of b or χ, the above elementary step is iterated until the system converges to a stationary state where the frequencies of the strategies fluctuate stably. Equilibrium frequencies of the strategies are obtained by averaging over 10 000 generations after a transient state of 100 000 generations.

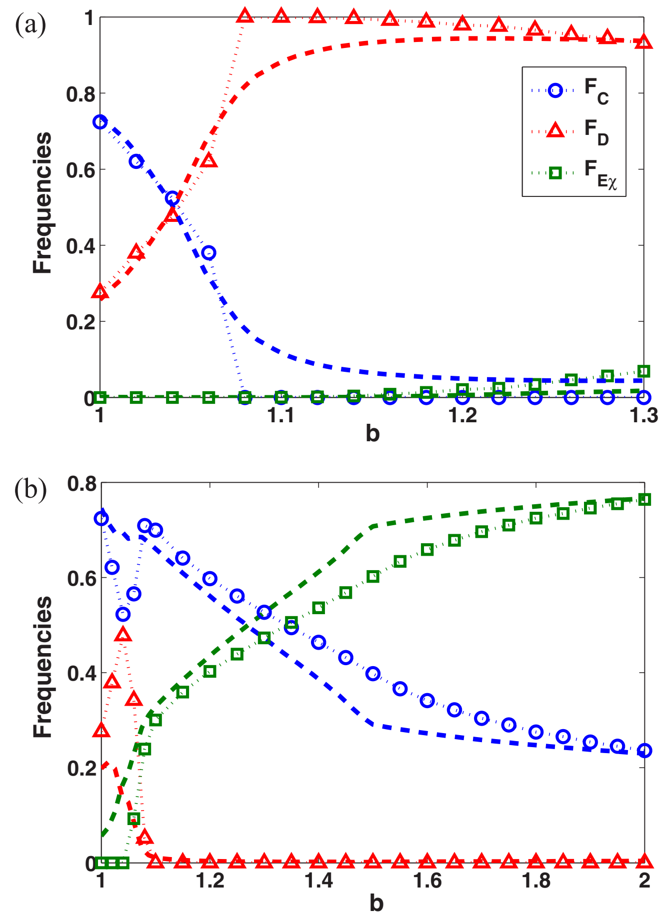

FIG. 1. Frequencies of cooperators (F_C), defectors (F_D), and extortioners (F_{E_χ}) as a function of the benefit factor b on the square lattice of size 100×100 for (a) $\chi = 1.5$ and (b) $\chi = 5.0$. The results are obtained over 20 independent runs. The dashed lines correspond to the predictions of the generalized mean-field approximation based on the 2×2-site clusters [18]. The extinction threshold of cooperation $b_C \approx 1.07(5)$ in Fig. 1(a).

III. RESULTS AND ANALYSIS

We first investigate how the frequencies of different strategies depend on the parameter b for fixed values of χ on the square lattice. For a small value of $\chi = 1.5$, as shown in Fig. 1(a), cooperators can coexist with defectors, and extortioners cannot survive in the population for sufficiently small $b < 1.1$. With the increase of b, cooperators will die out rapidly, while extortioners begin to arise and survive in the system. Actually, in this case the frequency of cooperation behaves as if extortioners have never existed in the system. However, for a large value of $\chi = 5.0$, we observe from Fig. 1(b) that things change dramatically, where cooperators are able to sustain in the population in the whole range of $1.0 < b < 2.0$, while defectors are always expelled out in the system for $b > 1.1$. Since larger χ means that cooperators

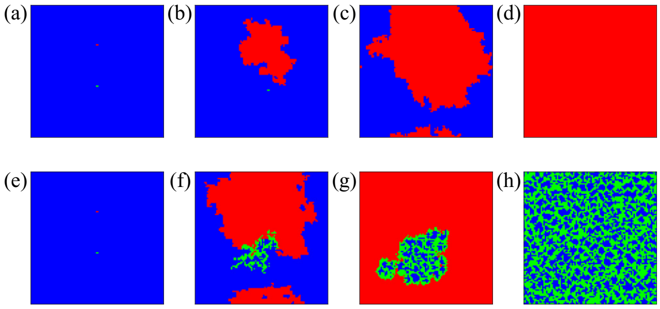

FIG. 2. Typical spatial distributions of C (blue, dark), D (red, gray), and E_χ (green, light gray) at some representative generations. (a, e) Initially, the whole population consist of cooperators except for two defectors and two extortioners. (b–d) Snapshots at $t = 500, 1000, 2000$ for $\chi = 1.5$ and $b = 1.4$. (f–h) Snapshots at $t = 1000, 2000, 10\,000$ for $\chi = 5.0$ and $b = 1.4$.

are more severely exploited by extortioners, the result appears counterintuitive at the first glance, which indicates that the involvement of extortioners plays a nontrivial role in the evolution of cooperation. It is worthy noting that the generalized mean-field approximation method based on 2×2-site clusters [18] predicts correctly the trend of the three strategies (in the stationary state).

In order to reveal the underlying mechanism that benefits the formation of cooperation, we check the pattern formation of different strategies during the evolutionary process. Figure 2 shows some representative snapshots starting from a special initial setting of the three strategies for $\chi = 1.5$ and $\chi = 5.0$ with $b = 1.4$. We have checked that qualitatively similar results can be obtained for other values of b. At the very beginning, the whole population is occupied by cooperators, except for two defectors and two extortioners, as illustrated in Figs. 2(a) and 2(e). According to the payoff matrix Eq. (1), with a very small $\chi = 1.5$, when meeting a cooperator, an extortioner always obtains much less payoff than a defector does. In such, it is quite hard for the extortion strategy to spread among the cooperators, in comparison to the defection strategy. This leads to the outcome that cooperators need to face defectors alone in most situations, and finally are get defeated, as depicted in Figs. 2(b)–2(d).

Surprisingly, the scenario changes markedly for a large $\chi = 5.0$. It is shown from Figs. 2(f)–2(h), since extortioners now exploit more from their cooperative neighbors, they can expand outward efficiently in the population before the invasion of defectors. Different from the relationship between C and D where cooperators always obtain negative payoffs from defectors, extortioners can provide small but positive payoffs to their cooperative neighbors, forming a snowdrift-like relationship. Therefore, extortioners and cooperators can form cross-like structures [5]; see Fig. 2(f). As time evolves, cooperators gather into small clusters, surrounded by extortioners who act as guardians and keep them away from defectors. What's more, once the $C - E_\chi$ alliance gains a firm foothold in the population, it begins to fight back and expands to the region occupied by defectors; see Fig. 2(g). As for defectors, due to being divided apart from cooperators and unable to obtain anything from extortioners, they can not receive any payoffs. In contrast, those extortioners on the boundary can still get positive payoffs from their cooperative neighbors inside. Consequently, defectors will be defeated and wiped out in the system by the $C - E_\chi$ alliance, as depicted in Fig. 2(h). It is worthy pointing out that neither cooperators nor extortioners alone can overcome defectors, but the alliance of them does.

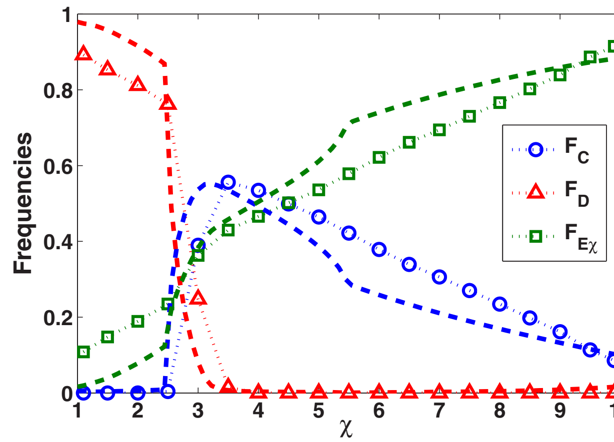

FIG. 3. Frequencies of the strategies F_C, F_D, and F_{E_χ} as a function of the extortion factor χ for $b = 1.4$ on the square lattice. The results are obtained over 20 independent runs. The dashed lines correspond to the predictions of the generalized mean-field approximation based on the 2×2-site clusters [18]. The extinction threshold of cooperation $\chi_C \approx 2.57(5)$.

From the results in Figs. 1 and 2, we realize that cooperators need to feed extortioners to some necessary extent (large enough χ) to boom themselves in turn. Does it mean that the larger χ is, the better for cooperation? Now, let us investigate the influence of the extortion factor χ on the evolution of cooperation. It is shown in Fig. 3 that when $\chi \leqslant 2.5$, extortioners cannot obtain enough benefits from their cooperative neighbors to expand successfully, which causes the extinction of cooperation and the coexistence of D and E_χ [45]. However, as χ increases beyond some threshold value, cooperation can emerge in the system with the aid of the snowdrift-like alliance mechanism discussed above. As long as defectors are present in the population, larger value of χ allows extortioners to defend the invasion of defectors more efficiently, through obtaining adequate benefit from cooperators, which not only keeps cooperation from extinction, but also launches a triumphant counter-attack against defection. However, when defectors are driven out of the population at some χ value, further increase of χ would do harm to the formation of cooperation, since the larger χ is, the more severely cooperators would be exploited by extortioners. Thus, it indicates that there exists an optimal value of χ best favoring the evolution of cooperation. The resonance-like behavior of F_C versus χ is also well predicted by the generalized mean-field approximation based on the 2×2-site clusters [18].

Now we start to investigate what would happen if the underlying interaction network is the BA scale-free network. It has been known that the heterogeneity in the connectivity network is a promotor of cooperation, if only C and D

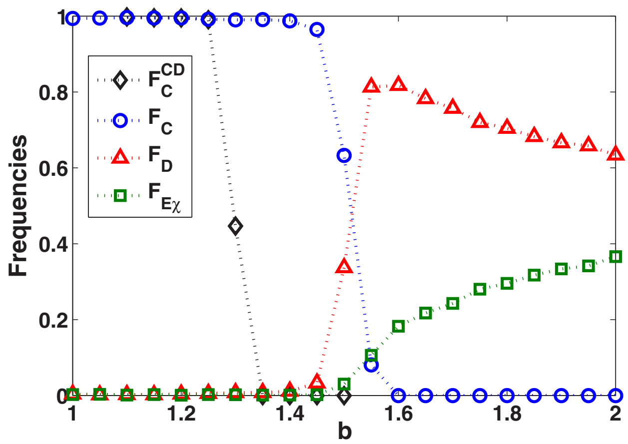

FIG. 4. Frequencies of different strategies as a function of the benefit factor b for $\chi = 1.5$ on the BA scale-free networks of size 10 000 and average degree $\langle k \rangle = 4$. The blue (dark) line with circles, red (gray) line with triangles and green (light gray) line with squares depict F_C, F_D, and F_{E_χ}, respectively. The black line with diamonds represents the frequency of C while there is no E_χ initially. All data are obtained from an average on 10 different networks realizations and 10 independent runs on each network.

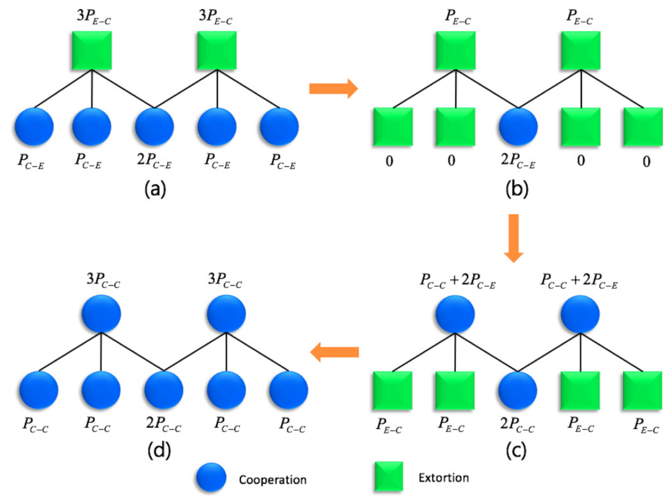

FIG. 5. The evolutionary process of our model on a typical subgraph of a scale-free social network, illustrating the bottom-up diffusion pattern of cooperation. The payoff of each node is labeled around it, where P_{A-B} denotes the payoff of A against B, A and $B \in C, D, E_\chi$.

are present in the system [14–16]. The basic mechanism is that, although some large degree nodes are prone to be occupied by defectors (due to their competition advantage over cooperators) at the beginning, they would induce their neighbors to follow them, which in turn leads to the gloomy prospect of their fates in the long term. On the other hand, cooperative hubs can support each other with their cooperative neighbors, reinforcing their advantage. Thus, cooperators can dominate in the population in a large regime of the parameter b [14,15].

When introducing extortioners into the scale-free network, this situation may change under the framework of replicator-like dynamics. Extortioners earn more but still leave positive payoffs to their cooperative neighbors, so they can act as catalysts to let cooperators survive on a heterogeneous network. It is shown in Fig. 4 that when extortioners evolve with cooperators and defectors on a BA scale-free network, under the help of extortioners, cooperators can dominate in the populations for a high value of b against defectors. This is different from the outcome on the square lattice where extortioners rapidly become extinct for $\chi = 1.5$. In what follows we will disclose the underlying evolution mechanism that the extortion strategy plays on the BA scale-free network.

First, let us study the evolution of extortion with cooperation on a typical heterogenous two-layer subgraph shown in Fig. 5, where there are two hubs with degree k that connect with some small-degree leaves and have a common neighbor. Initially, the two hubs are extortioners and other small-degree leaves are cooperators as shown in Fig. 5(a), through which we try to disclose how the cooperation diffuses from small-degree leaves to large-degree hubs. According to Eq. (1), the payoff of an extortioner is the χ-times surplus of her cooperative neighbor, $P_{E-C} = \chi P_{C-E}$. Hence, the accumulated payoff of an extortionate hub is much higher than all cooperative leaves, and some of them will adopt strategy E_χ, driven by Eq. (2), which in turn gives rise to the decrease of the hubs' payoffs. In the configuration shown in Fig. 5(b) where only the common neighbor of the hubs remains cooperative, the payoff of the cooperator is higher than the two hubs if $\chi < N_{C-E}$, and the competitive advantage between the leaf node and the hubs is reversed. Here, N_{C-E} is the number of extortionate neighbors around the cooperator. Once the hubs turn into cooperators by chance as shown in Fig. 5(c), they will attract the extortionate leaves to adopt C, resulting in a stable cooperation state of the system, Fig. 5(d). Thus, cooperation is very likely to diffuse from leaves to hubs, establishing a bottom-up mechanism to facilitate cooperation. It is worth pointing out that with the presence of extortioners it doesn't require the cooperators to occupy hub nodes initially and gather together to form a top-down diffusion pattern of cooperation, as exemplified in previous work where only cooperators and defectors are involved in the games [14–16].

Then, we study this bottom-up evolutionary mechanism of cooperation with defection and extortion strategies on the BA scale-free network. Initially, all nodes whose connectivity degrees are larger than 4 are assigned as defectors or extortioners with equal probability and the remaining small-degree nodes as cooperators. In doing so, the way in which the cooperative behavior diffuses on the scale-free network under the help of extortion strategy can be observed. It is shown that starting with all small-degree nodes adopting cooperation strategy, most of them will be replaced by other large-degree nodes' strategies in the first few Monte Carlo steps, which leads to the decrease of F_C as well as the increase of F_D and F_E, as shown in Fig. 6(a). Nevertheless, from Figs. 6(b)–6(d) we observe that at the 10th generation, there is a fraction of cooperators starting to occupy the large-degree nodes, which used to be occupied by extortioners. This inconspicuous transition leads to a tremendous consequence that under the help from extortioners, cooperators continue occupying nodes from small to large degree until they dominate in the network. The reason is that both defection and

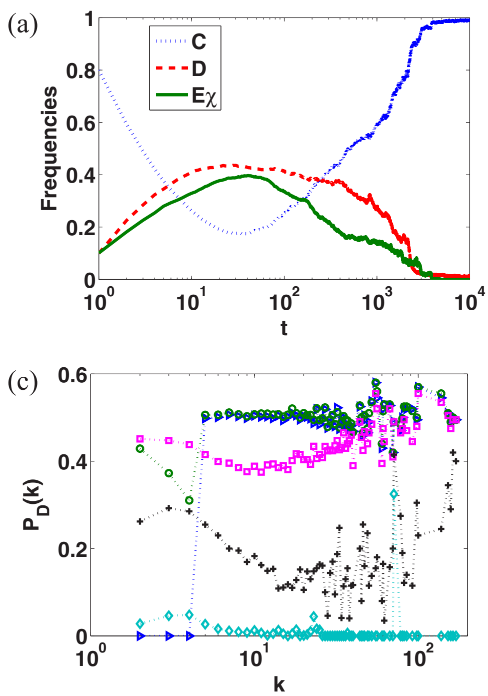

FIG. 6. (a) Frequencies of different strategies as a function of the time step t for $b = 1.4$ and $\chi = 1.5$ on the BA scale-free networks, where initially the nodes whose degrees are larger than 4 are randomly set as defectors or extortioners, and the rest small-degree nodes are cooperators. (b–d) The evolution of the fraction of cooperators $[P_C(k)]$, defectors $[P_D(k)]$, and extortioners $[P_{E\chi}(k)]$ per degree at some representative time steps ($t = 1, 10, 100, 1000, 10\,000$) with $b = 1.4$ and $\chi = 1.5$. The data are obtained by averaging over 200 independent runs on a BA scale-free network with 10 000 nodes and $\langle k \rangle = 4$.

extortion strategies perform worst when playing with the same strategies as themselves, resulting in the negative feedback between their gained payoffs and frequencies in the population. Particularly, we find that the involvement of extortioners leads to a bottom-up mechanism for the evolution of cooperation, in contrast to previous work [14], where the cooperative hubs defeat defective hubs, establishing a top-down mechanism for the persistence of cooperation.

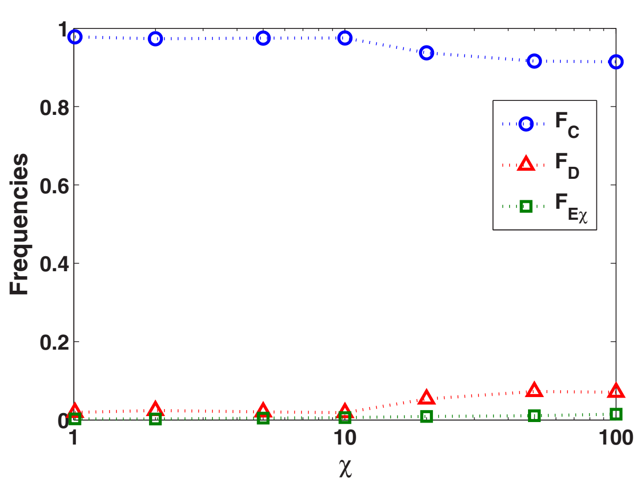

FIG. 7. The frequencies of the three strategies F_C, F_D, and F_{E_χ} as a function of the extortion factor χ for $b = 1.4$ on the BA scale-free network with 10 000 nodes and $\langle k \rangle = 4$. The data are obtained by averaging over 10 different BA scale-free networks and 10 independent runs for each network.

Finally, we investigate the influence of the extortion factor χ on the game dynamics for fixed value of b on the BA scale-free networks. Different from the situation on the square lattice where the extortion factor χ has nontrivial influence on the evolution of cooperation, it is shown from Fig. 7 that χ has slight influence on the evolution of cooperation on the scale-free network. Extortioners can help cooperators to dominate the heterogeneous network both at low and high value of χ. However, when χ becomes greater than 10, cooperators obtain less benefit from extortioners, which in turn decreases extortioners' payoff and weakens the role of the catalysts. As a result, defectors may occasionally overcome cooperators and spread quickly on the scale-free network.

IV. CONCLUSIONS AND DISCUSSIONS

In summary, we have studied the evolution of cooperation in structured populations by considering the competition of unconditional cooperation, unconditional defection, and extortion on either the square lattice or the BA scale-free networks under the replicator-like dynamics. We found that the involvement of extortion leads to new routes to the emergence and persistence of cooperation, which depends on the spatial structure of the underlying interaction pattern. In particular, on regular lattice, cooperation can be pregnant in the sea of extortioners for appropriate extortion factor χ, and the alliance of them is able to outperform those surrounding defectors. The enhancement of cooperation behaves as a resonance-like phenomenon by varying χ. On heterogeneous scale-free networks, high cooperation level can be established and maintained via a

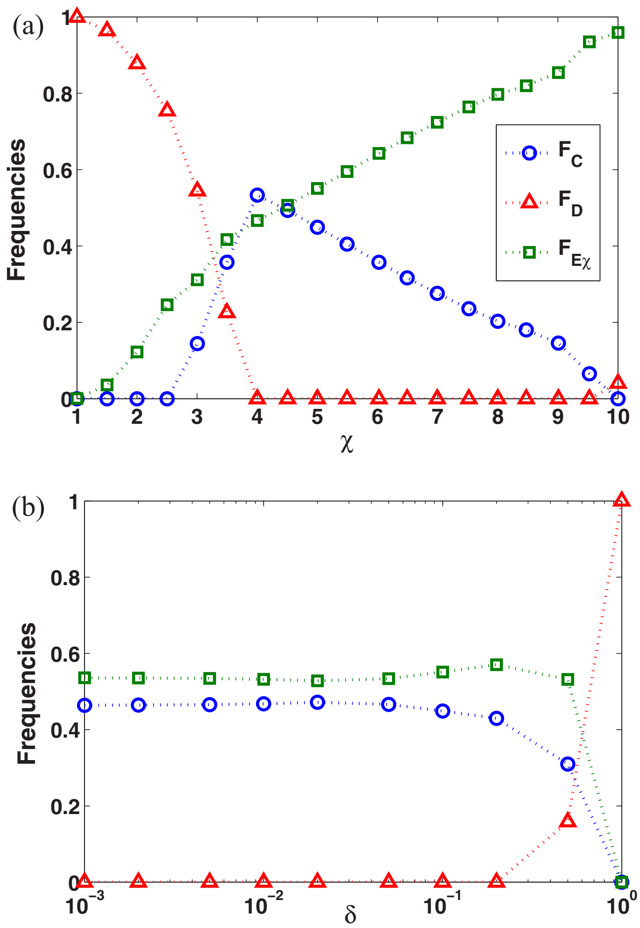

FIG. 8. Frequencies of cooperators (F_C), defectors (F_D) and extortioners (F_{E_χ}) (a) as a function of the extortion factor χ for $b = 1.4$, $\delta = 0.1$ and (b) as a function of the noise factor δ for $b = 1.4$, $\chi = 5.0$ on the square lattice of size 100×100. The results are obtained over 20 independent runs.

bottom-up mechanism, where the cooperators on small degree nodes are capable of surpassing the extortioners on the hubs during the evolutionary process. With the assistance from extortioners, cooperators can dominate the population in a more wider range of the game parameter, as compared to the scenario without extortioners in the system.

In the main text we investigated the evolution of strategies under the classical framework of replicator-like dynamics, which considers individuals with strong rationality, i.e., only a strategy with lower payoff can be replaced by another strategy with higher payoff. Actually, we have checked our results for the weak rationality case through a revised replicator-like dynamics model: after playing games with all the neighbors, an individual x randomly selects one neighbor y, and imitates y's strategy with the probability

$$W(S_x \leftarrow S_y) = \max\left\{0, \frac{P_y - P_x + \delta \cdot H}{\max(k_x,k_y)\cdot H + \delta \cdot H}\right\}, \quad (3)$$

where the parameter δ describes the bounded rationality of the individuals or characterizes the noise of the environment. Through introducing the noise factor δ into the update process, an inferior strategy may also have the probability to be imitated by a more successful one. We found from Fig. 8(a) that the resonance-like behavior of F_C versus χ on the square lattice also exists in the bounded rationality case with $\delta = 0.1$. And it is shown from Fig. 8(b) that for $\delta \leqslant 0.2$, the catalyst effect of extortion works perfectly to promote cooperation on the square lattice. For high value of $\delta > 0.2$, which implies individuals become extremely irrational, the defective behavior increases in the networked systems. Hence, our conclusions are robust for the bounded rationality case in some certain noisy environment. According to Eq. (2), the imitation cannot occur when two individuals have the same payoff. We have also validated our results for the neutral drift case, i.e., an individual may probably adopt a neighbor's strategy when both of them own the equal payoff, and found that extortion can still promote cooperation.

The theory of ZD strategies significantly enriches the diversity of evolutionary game strategies and provides perspectives to study the population dynamics, which may help us understand the confusing ubiquity of cooperation in nature. In addition, recent studies have found that ZD strategies can efficiently enforce the long-term payoff relationship in experiments while playing with human players and extortioners have been identified in some social dilemmas [46–48]. Therefore, the investigation of the evolution of ZD strategies in populations may not only help us better comprehend diverse phenomena in the natural world such as the emergence of cooperation, but also shed light on the exploration of human behavior and play an important role in the promotion of cooperative behavior in social systems.

ACKNOWLEDGMENTS

The authors thank the anonymous reviewers for their constructive suggestions to help improve this paper. This work was supported by the National Natural Science Foundation of China (Grants No. 61273223, No. 61374053, No. 61473060, No. 11475074, and No. 11575072), the Fundamental Research Funds for the Central Universities (Grant No. ZYGX2016J192) and Hong Kong Scholars Program (Grants No. XJ2013019 and No. G-YZ4D), and the Open Project Program of State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, China (Grant No.Y5KF201CJ1), Major Project of National Social Science Foundation (Grant No. 12 & ZD218).

[1] M. Smith, *Evolution and the Theory of Games* (Cambridge University Press, Cambridge, UK, 1982).
[2] M. A. Nowak, *Evolutionary Dynamics: Exploring the Equations of life* (Harvard University Press, Cambridge, MA, 2006).
[3] K. Sigmund, *The Calculus of Selfishness* (Princeton University Press, Princeton, NJ, 2010).
[4] M. A. Nowak and R. May, Nature **359**, 826 (1992).
[5] C. Hauert and M. Doebeli, Nature **428**, 643 (2004).

[6] R. Axelrod, *The Evolution of Cooperation* (Basic Books, New York, 1984).
[7] M. A. Nowak, Science **314**, 1560 (2006).
[8] D. G. Rand and M. A. Nowak, Trends Cogn. Sci. **17**, 413 (2013).
[9] G. Szabó and C. Tőke, Phys. Rev. E **58**, 69 (1998).
[10] G. Szabó, J. Vukov, and A. Szolnoki, Phys. Rev. E **72**, 047107 (2005).
[11] C. Hauert and G. Szabó, Am. J. Phys. **73**, 405 (2005).
[12] F. C. Santos, J. F. Rodrigues, and J. M. Pacheco, Phys. Rev. E **72**, 056128 (2005).
[13] J. Vukov, G. Szabó, and A. Szolnoki, Phys. Rev. E **73**, 067103 (2006).
[14] F. C. Santos and J. M. Pacheco, Phys. Rev. Lett. **95**, 098104 (2005); F. C. Santos, J. M. Pacheco, and T. Lenaerts, Proc. Natl. Acad. Sci. USA **103**, 3490 (2006).
[15] J. Gómez-Gardeñes, M. Campillo, L. M. Floría, and Y. Moreno, Phys. Rev. Lett. **98**, 108103 (2007); J. Poncela, J. Gómez-Gardeñes, L. M. Floría, and Y. Moreno, New J. Phys. **9**, 184 (2007).
[16] Z. Z. Rong, X. Li, and X. F. Wang, Phys. Rev. E **76**, 027101 (2007).
[17] H. X. Yang, Z. X. Wu, and W. B. Du, Europhys. Lett. **99**, 10006 (2012).
[18] G. Szabó and G. Fáth, Phys. Rep. **446**, 97 (2007).
[19] M. Perc and A. Szolnoki, BioSystems **99**, 109 (2010).
[20] M. Perc, J. Gómez-Gardeñes, A. Szolnoki, L. M. Floría, and Y. Moreno, J. R. Soc. Interface **10**, 20120997 (2013).
[21] A. Szolnoki and M. Perc, New J. Phys. **10**, 043036 (2008).
[22] M. Perc and A. Szolnoki, Phys. Rev. E **77**, 011904 (2008).
[23] A. Szolnoki, Z. Wang, and M. Perc, Sci. Rep. **2**, 576 (2012).
[24] Z. X. Wu, Z. H. Rong, and M. Z. Q. Chen, Europhys. Lett. **110**, 30002 (2015).
[25] Z.-X. Wu, X.-J. Xu, Z.-G. Huang, S.-J. Wang, and Y.-H. Wang, Phys. Rev. E **74**, 021107 (2006).
[26] H. X. Yang, W. X. Wang, Z. X. Wu, Y. C. Lai, and B. H. Wang, Phys. Rev. E **79**, 056107 (2009).
[27] M. Perc and Z. Wang, PLoS ONE **5**, e15117 (2010).
[28] H. Ohtsuki, M. A. Nowak, and J. M. Pacheco, Phys. Rev. Lett. **98**, 108106 (2007).
[29] Z.-X. Wu, Z. H. Rong, and P. Holme, Phys. Rev. E **80**, 036106 (2009).
[30] Z. H. Rong, Z. X. Wu, and G. Chen, Europhys. Lett. **102**, 68005 (2013).
[31] X. J. Chen and L. Wang, Phys. Rev. E **77**, 017103 (2008).
[32] Y. Liu, X. Chen, L. Zhang, L. Wang, and M. Perc, PLoS ONE **7**, e30689 (2012).
[33] W. H. Press and F. J. Dyson, Proc. Natl. Acad. Sci. USA **109**, 10409 (2012).
[34] C. Adami and A. Hintze, Nat. Commun. **4**, 2193 (2013).
[35] C. Hilbe, M. Nowak, and K. Sigmund, Proc. Natl. Acad. Sci. USA **110**, 6913 (2013).
[36] C. Hilbe, M. A. Nowak, and A. Traulsen, PLoS ONE **8**, e77886 (2013).
[37] A. Szolnoki and M. Perc, Phys. Rev. E **89**, 022804 (2014).
[38] A. Szolnoki and M. Perc, Sci. Rep. **4**, 5496 (2014).
[39] Z. X. Wu and Z. Rong, Phys. Rev. E **90**, 062102 (2014).
[40] Z. H. Rong, Z. X. Wu, D. Hao, M. Z. Q. Chen, and T. Zhou, New J. Phys. **17**, 033032 (2015).
[41] Z. H. Rong, Q. Zhao, Z. X. Wu, T. Zhou, and C. K. Tse, Eur. Phys. J. B **89**, 166 (2016).
[42] J. Hofbauer and K. Sigmund, *Evolutionary Games and Population Dynamics* (Cambridge University Press, Cambridge, 1998).
[43] H. Gintis, *Game Theory Evolving* (Princeton University Press, Princeton, NJ, 2000).
[44] A. L. Barabási and R. Albert, Science, **286**, 509 (1999).
[45] The reason D and E_χ coexist here while D can dominate the whole population in Fig. 2(d) is that they start from different initial distribution of strategies. When there are only a very small amount of extortioners in the population initially, the few extortioners are difficult to diffuse and may become extinct on square lattice for low value of χ. We have checked the results and found that the frequencies of different strategies are weakly dependent on the initial distribution of strategies when initially there are sufficient amount of extortioners.
[46] C. Hilbe, T. Röhl, and M. Milinski, Nat. Commun. **5**, 3976 (2014).
[47] Z. Wang, Y. Zhou, J. W. Lien, J. Zheng, and B. Xu, Nat. Commun. **7**, 11125 (2016).
[48] M. Milinski, C. Hilbe, D. Semmann, R. Sommerfeld, and J. Marotzke, Nat. Commun. **7**, 10915 (2016).