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Dynamic of interactive model for information propagation across social networks media

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Abstract

Controlling information diffusion or propagation through social networks can be challenging when dealing with information related to a subject of highest interest for the public. The complexity level of control depends on subject importance, users' dynamic, and network structure. When two published messages or pieces of information share the same interest for targeted readers, analyzing their propagation dynamic for control and prediction is of great interest. This article proposes to model, based on a modified interactive system with Holling type functional response, the dynamic of underlying relationship between two broadcasted messages traveling through social networks media. We showed in the qualitative analysis of the proposed model that system could be stable at certain conditions, and the model-system exhibited very rich dynamical behavior. Numerical simulation results validated theoretical analyses and suggested adapting resources harvesting and assimilation efficiency for an authoritative message to stabilize the system and control the dissemination of information in a closed environment.

Keywords: Information propagation; Social network; Competitive interaction; Logistic model; Holling type II; Stability analysis

1 Introduction

Avoiding overdiffusion or propagation of broadcasted messages or information in social networks media or platform can be necessary and needed in preventing disinformation, panic, or overreaction due to content sensibility in a closed environment. On most of social media platforms, information propagation may follow a random pattern relying on the size of the network, users' dynamic, and publishers' ties or importance [1–4]. It has become challenging to predict and control the speed of diffusion and dissemination of information in larger scale and complex networks such as today's social networks. The omnipresence of connectivity and wide spread of intelligent devices are among multiple reasons that may explain this complexity. As investigated by numerous authors, most of the studies related to information propagation, rumors diffusion, and so forth have been focusing on information speed of diffusion, readership growth rate, and network topology. Some researchers investigated node properties to analyze the influence each node has on

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information dissemination in a period of crisis for example, relying on epidemic control models and social network analysis techniques and methods [5–9].

We are interested in this article in analyzing the influence different pieces of information may have on each other when they are related to the same topic and have the same interest for the audience or readership. Identifying the type and nature of underlying relationship between interacting entities is a key in controlling and predicting system behavior as stipulated in many published articles in related literature [10–15].

In this article, we propose to consider the impact of social network users' behavior on information propagation dynamic when two influential publishers publish two messages or pieces of information on a social media platform. We consider the published messages to be related to the same topic, thus sharing relatively the same interest for readers or followers. The published messages may reach a larger audience, depending on publishers' ties and importance in respect to the number of followers. Readers may follow both publishers; consequently, one published message related to the same subject may drive readers to do more comparisons for enrichment of viewpoint and knowledge about the respective subject. As a result, one published message may lead to discovery and contact with more messages related to the same topic from different publishers. Depending on how reliable readers consider respective publishers, they will repost, transmit, or recommend the piece of information to their own followers [16–20]. This phenomenon can be assimilated to a predator-prey type relationship in which messages or information that increase respective readership per time unit could be considered as predator. As in the classical dynamic social network analysis, users or nodes have random behavior and may move to different locations, virtual groups, etc. We consider the publishers to share audience and the readers to join randomly any publishers' open group.

Traditional logistic Lotka–Volterra based interactive systems are commonly used to model interactions occurring in a system where entities share available resources. The advantage of such systems is that they exhibit rich dynamical behavior and have many applications in the real world, such as economic ties, interconnected markets, applied engineering sciences, ecology, etc. Models with Holling type functional responses are well spread and there are large varieties of modified models adjusted to formalize specific ties or relationship in dynamical systems. Depending on studied systems and underlying interaction types, the outcome of interaction may be simple or complex. Holling type functional response commonly allows better control of resources accessibility, harvesting time, assimilation efficiency, and so forth [21–24].

Controlling rumor and fake news overdiffusion through social media is a recurrent problem that needs to be addressed from different perspectives for control purposes. Measuring and reducing information speed of diffusion in nowadays society have become challenging due to social network popularity and widespread Internet network. The upcoming of next generation mobile and intelligent devices along with the Internet of things may even bring more challenges from management and control standpoint. This investigation proposes an insight into network resources administration and information diffusion. Whether we deal with real news or rumors, this article provides a new angle of investigation to describe and solve existing issues and challenges from resources optimization and control perspectives. Results of this work could be used to determine the effect authoritative information could have on related persistent propagating rumors traveling through social networks media, such as Weibo, WeChat, etc. Particularly, in a period of

crisis where a decision about the content related to national security or social wellbeing has to be made to establish or restore the truth. The main motivation of this investigation is to provide supporting evidence on the importance of controlling overdiffusion of sensible and potentially dangerous contents across social media platforms and promoting the truth.

By performing qualitative analysis of the proposed competitive model, we found that, under certain conditions, the system could be stable and both published pieces of information could coexist peacefully. Furthermore, the dynamic of this particular competition in a closed environment is impacted directly by readers' behavior, content nature, the importance of related subject in respect to readers' interest, and network state in terms of resources availability as shown in numerical simulation results. Adjusting diffusion efficiency or publishing higher interest information through certain nodes may boost given message propagation efficiency and improve the publisher's esteem or reliability.

2 Model

Let M_1 and M_2 be the number of views of respectively the first and second message at time t . If we consider there is interconnection between readers, then people who read M_1 first may or may not look at M_2 content for crosschecking purpose for example and vice-versa. This behavior depends on content attractiveness or interest for the reader. Considering there is an upper limit in the number of views for each posted message, we formalize this limitation using logistic terms in both M_1 and M_2 . Each message will increase respective views or population size, using ecology terms, if the number of views increases per time unit, the rate of increase being proportional to the per capita total number of views at time t . A model system is given by

$$\begin{aligned} \frac{dM_1}{dt} &= M_1 \left[a_1(V - nM_1) \left(1 - \frac{M_1}{V} \right) - \frac{a_2M_2}{1 + a_3M_1} \right], \\ \frac{dM_2}{dt} &= M_2 \left[b_1 \left(1 - \frac{mM_2}{V} \right) + \frac{b_2M_1}{1 + a_3M_1} \right], \end{aligned} \tag{1}$$

where $a_1, a_2, a_3, b_1, b_2, n, m,$ and V are positive constant parameters, a_1 and b_1 represent respectively the natural growth coefficients of M_1 and M_2 . a_2 corresponds to the interaction effect of M_2 on M_1 , and b_2 is positive feedback resulting from this interaction. a_3 formalizes assimilation efficiency and harvesting effort in respect to the time needed to capture and consume resources. n is a control parameter modeling the threshold when M_1 reaches the critical number of views. m is a control parameter modeling the effect of promotion from which M_2 benefits. V is the maximum number of views each message can reach. This factor is incorporated in the proposed model for practical and analysis purposes, in respect to a social network's finite number of views.

It is clear that:

- (i) Both M_1 and M_2 increase density or number of views as far as $0 < M_1(t) < V < V/n$, and $0 < M_2(t) < V < V/m$ as far as $0 < m, n < 1$.
- (ii) $a_2M_2/(1 + a_3M_1)$ value depends on a_2 and a_3 for a larger M_1 population or the number of views. M_2 will thrive only if interaction is intensive, meaning when there is a significant proportion of readers who only read one message and never double check, trusting respective publisher. On the other hand, M_1 will suffer less from predation if M_2 is weaker or has relatively less views.

Set

$$\begin{aligned} \frac{dM_1}{dt} &= f_1(M_1, M_2), \\ \frac{dM_2}{dt} &= f_2(M_1, M_2), \end{aligned} \tag{2}$$

such that $f_1(M_1, M_2)$ and $f_2(M_1, M_2)$ are continuously derivable functions for $M_1, M_2 > 0$.

Then we can write

$$\begin{aligned} \frac{\partial f_1}{\partial M_1} &= 3a_1nM_1^2 - 2a_1(n+1)M_1 + a_1V - \frac{a_2M_2}{(1+a_3M_1)^2}, \\ \frac{\partial f_2}{\partial M_2} &= b_1 - \frac{2b_1nM_2}{V} + \frac{b_2M_1}{1+a_3M_1}, \\ \left| \frac{\partial f_1}{\partial M_1} \right| &= \left| a_1(3nM_1^2 + V) - \left[2a_1(n+1)M_1 + \frac{a_2M_2}{(1+a_3M_1)^2} \right] \right|, \\ &< |a_1(3nM_1^2 + V)| \leq a_1V(3nV + 1); \\ \left| \frac{\partial f_2}{\partial M_2} \right| &= \left| b_1 + \frac{b_2M_1}{1+a_3M_1} - \frac{2b_1nM_2}{V} \right| < \left| b_1 + \frac{b_2M_1}{1+a_3M_1} \right| < b_1 + \frac{b_2}{a_3}. \end{aligned} \tag{3}$$

$\forall t \rightarrow \infty$, solutions of system (1) are unique according to the Lipschitz condition.

Furthermore, applying the Poincaré–Bendixson criterion, we have

$$\begin{aligned} \operatorname{div}(f_1, f_2) &= \frac{\partial f_1}{\partial M_1} + \frac{\partial f_2}{\partial M_2} \\ &= 3a_1nM_1^2 + a_1V + b_1 + \frac{b_2M_1}{1+a_3M_1} \\ &\quad - \left[2a_1(n+1)M_1 + \frac{2b_1nM_2}{V} + \frac{a_2M_2}{(1+a_3M_1)^2} \right] \\ &\neq 0. \end{aligned} \tag{4}$$

This indicates that system (1) has at least one periodic orbit lying in the phase plane (M_1, M_2) for a given set of parameters value according to the Poincaré–Bendixson criterion.

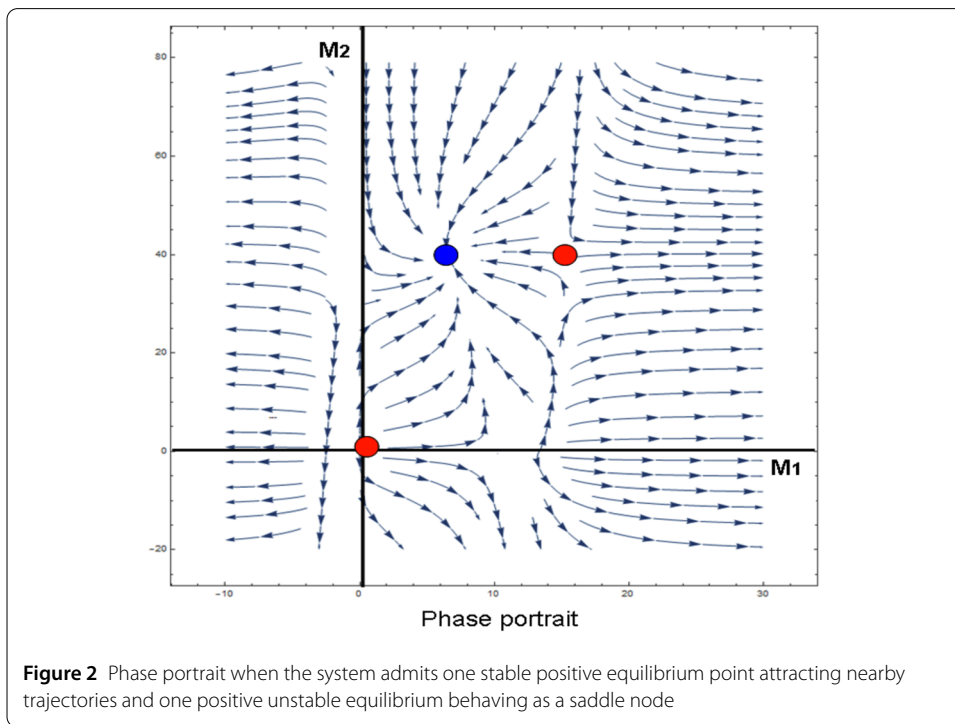
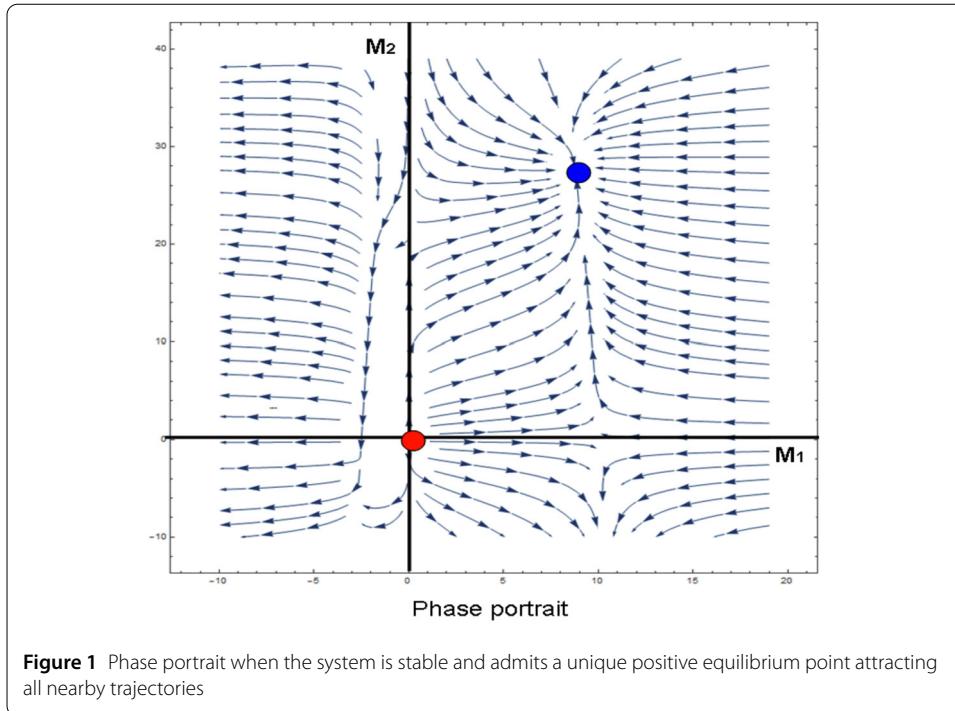
3 Model steady state

In this section, we describe a steady state equilibrium of the system.

(i) The zero growth isoclines equations are given by

$$\begin{cases} F = a_1a_3nM_1^3 + (a_1n - a_1a_3nV - a_1a_3V)M_1^2 + (a_1a_3V^2 - a_1nV - a_1V)M_1 \\ \quad - a_2VM_2 + a_1V^2 = 0, \\ G = V(1 - a_3)M_1 - nM_2 + a_2mM_1M_2 + V = 0. \end{cases} \tag{5}$$

Based on (5), we know that interaction happens. The system may admit more than one positive solution in the first quadrant as portrayed in Fig. 1 and Fig. 2. The ideal scenario is to choose parameter value such that the intersection point of the two isoclines lies in the positive quadrant.



(ii) The unique positive equilibrium point of the system can be computed solving (5). From G we obtain

$$M_2^* = \frac{V(1 + M_1^* + a_3 M_1^*)}{n - a_2 m M_1^*}, \quad n > a_2 m M_1^*,$$

$$t \rightarrow \infty, \quad M_1(t) < \frac{n}{a_2 m}.$$

(6)

After substituting in F and rearranging, we get

$$p_0 M_1^4 + p_1 M_1^3 + p_2 M_1^2 + p_3 M_1 + p_4 = 0, \quad (7)$$

where

$$\begin{aligned} p_0 &= -a_1 a_2 n m, \\ p_1 &= -a_1 [a_2 m n^2 + a_2 m (n - a_3 n V - a_3 V)], \\ p_2 &= a_1 n (n + n a_3 V - a_3 V) - a_1 a_2 m V (a_3 V - n - 1), \\ p_3 &= V [a_1 n (a_3 V - n - 1) - a_2 V (a_3 + 1) - a_1 a_2 m V], \\ p_4 &= (a_1 n - a_2) V^2. \end{aligned}$$

Equation (7) could be reduced by changing variables to

$$X^4 + \mu_0 X^3 + \mu_1 X + \mu_2 = 0, \quad (8)$$

where

$$M_1 = X - \frac{p_1}{4p_0},$$

and

$$\begin{aligned} \mu_0 &= \frac{p_2}{p_0} - \frac{3p_1^2}{8p_0^2}, \\ \mu_1 &= \frac{p_3}{p_0} - \frac{p_1 p_2}{2p_0^2} + \frac{p_1^3}{8p_0^3}, \\ \mu_2 &= \frac{p_4}{p_0} - \frac{p_1 p_3}{4p_0^2} + \frac{p_1^2 p_3}{16p_0^3} - \frac{3p_1^4}{256p_0^4}. \end{aligned}$$

Take a variable s satisfying the following resolving cubic equation:

$$8s^3 - 4\mu_0 s^2 - 8\mu_2 s + (3\mu_0 \mu_2 - \mu_1^2) = 0. \quad (9)$$

It follows

$$(X^2 + s)^2 - [(2s - \mu_0)X^2 - \mu_1 X + s^2 - \mu_2] = 0 \quad (10)$$

and

$$(2s - \mu_0)X^2 - \mu_1 X + s^2 - \mu_2 = (2s - \mu_0)(X - X^+)(X - X^-). \quad (11)$$

Under the constraint $X^+ = X^-$, we can write

$$\left(X^2 + s + \sqrt{2s - \mu_0} X - \frac{\mu_1}{2\sqrt{2s - \mu_0}} \right) \left(X^2 + s - \sqrt{2s - \mu_0} X + \frac{\mu_1}{2\sqrt{2s - \mu_0}} \right) = 0. \quad (12)$$

Equation (8) admits four solutions given by

$$X_{1,2} = -\frac{1}{2}\sqrt{2s - \mu_0} \pm \frac{1}{2}\sqrt{-2s - \mu_0 + \frac{2\mu_1}{\sqrt{2s - \mu_0}}}, \tag{13}$$

$$X_{3,4} = \frac{1}{2}\sqrt{2s - \mu_0} \pm \frac{1}{2}\sqrt{-2s - \mu_0 - \frac{2\mu_1}{\sqrt{2s - \mu_0}}}. \tag{14}$$

From (13) and (14) we deduct

$$M_1^k = X_k - \frac{\mu_1}{4\mu_0}, \quad k = 1, 2, 3, 4. \tag{15}$$

Then the steady state equilibrium is given by

$$(M_1^*, M_2^*) = \left(M_1^k, \frac{V(1 + M_1^k + a_3 M_1^k)}{n - a_2 m M_1^k} \right), \quad k = 1, 2, 3, 4. \tag{16}$$

4 Model stability analysis

In this section, we determine stability conditions around the system steady state equilibrium and analyze interaction outcome.

Let the Jacobian matrix be

$$J = \begin{pmatrix} O & P \\ Q & R \end{pmatrix}, \tag{17}$$

where

$$\begin{aligned} O &= 3a_1 n \bar{M}_1^2 - 2a_1(n + 1)\bar{M}_1 + a_1 V - \frac{a_2 \bar{M}_2}{(1 + a_3 \bar{M}_1)^2}, \\ P &= -\frac{a_2 \bar{M}_1}{1 + a_3 \bar{M}_1}, \quad Q = \frac{b_2 \bar{M}_2}{(1 + a_3 \bar{M}_1)^2}, \\ R &= b_1 - \frac{2b_1 \bar{M}_2}{V} + \frac{b_2 \bar{M}_1}{1 + a_3 \bar{M}_1}. \end{aligned} \tag{18}$$

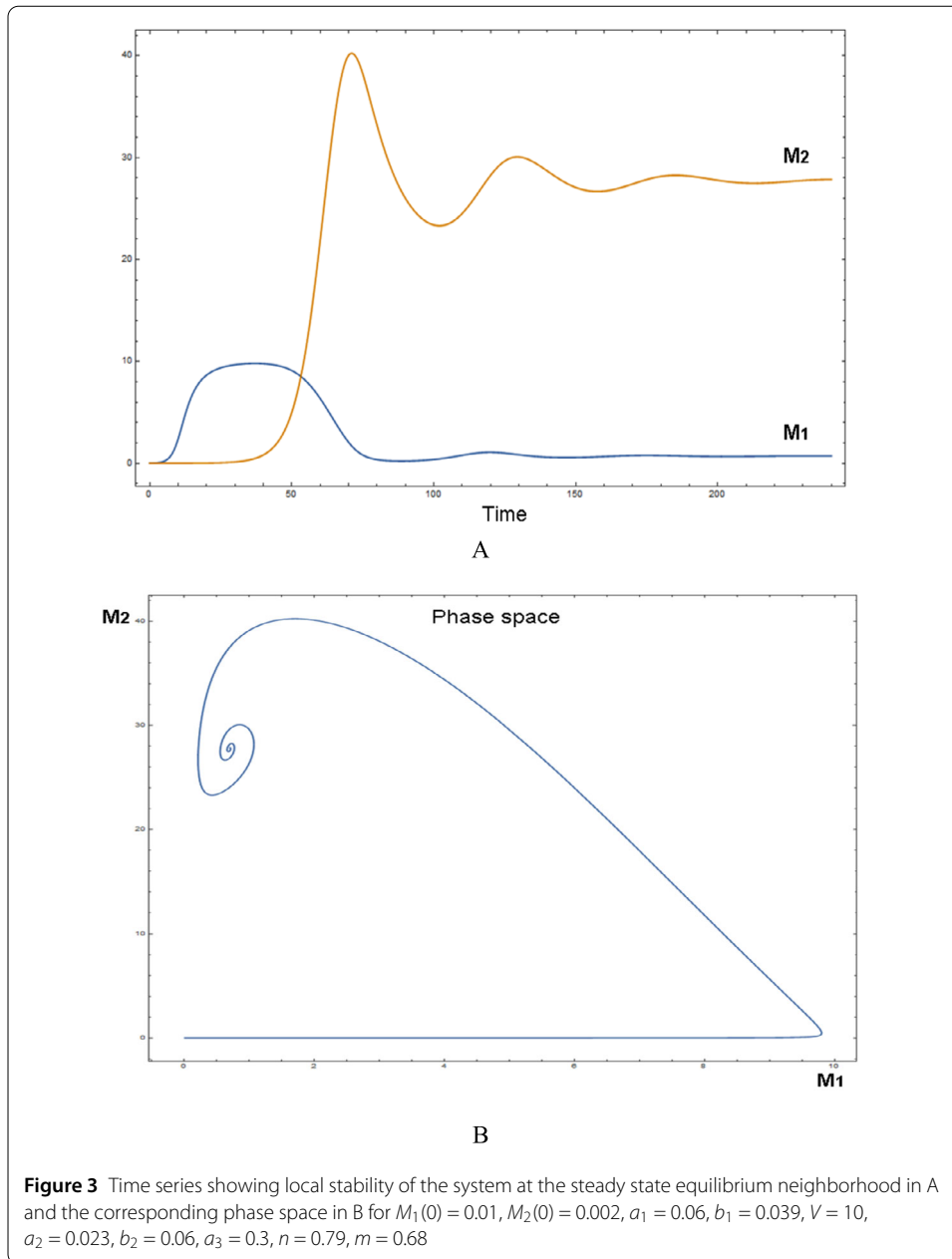
1—At the origin, we have

$$J(0, 0) = \begin{pmatrix} a_1 V & 0 \\ 0 & b_1 \end{pmatrix}. \tag{19}$$

The origin is always unstable, the polynomial equation admits two positive roots and (19) determinant is greater than zero.

2—At the positive equilibrium point, we have

$$\begin{aligned} O &= 3a_1 n M_1^{*2} + a_1 V - [2a_1(n + 1)M_1^* + \frac{a_2 M_2^*}{(1 + a_3 M_1^*)^2}], \\ P &= -\frac{a_2 M_1^*}{1 + a_3 M_1^*}, \quad Q = \frac{b_2 M_2^*}{(1 + a_3 M_1^*)^2}, \\ R &= b_1 + \frac{b_2 M_1^*}{1 + a_3 M_1^*} - \frac{2b_1 M_2^*}{V}. \end{aligned} \tag{20}$$



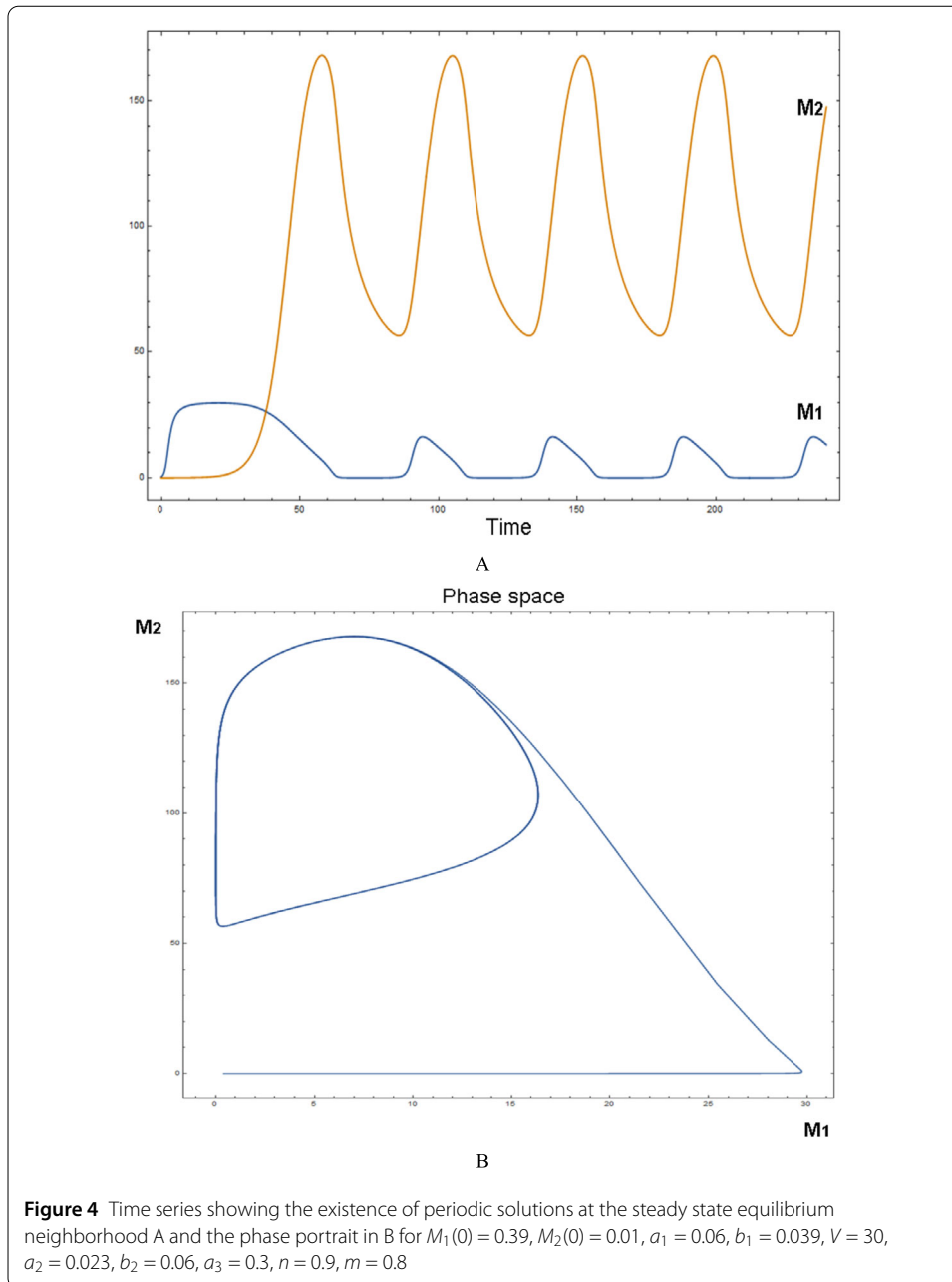
The characteristic polynomial equation is given by

$$\lambda^2 - (O + R)\lambda + OR - PQ = 0. \tag{21}$$

The system is asymptotically stable at the neighborhood of the steady state equilibrium only if $O + R < 0$ and $OR - PQ > 0$.

In case equation (21) admits complex conjugate imaginary roots of the form $\lambda = \mu \pm i\omega$, we have

$$\begin{cases} \mu^2 - \omega^2 - \mu(O + R) + OR - PQ = 0, \\ 2\mu = O + R, \end{cases} \tag{22}$$

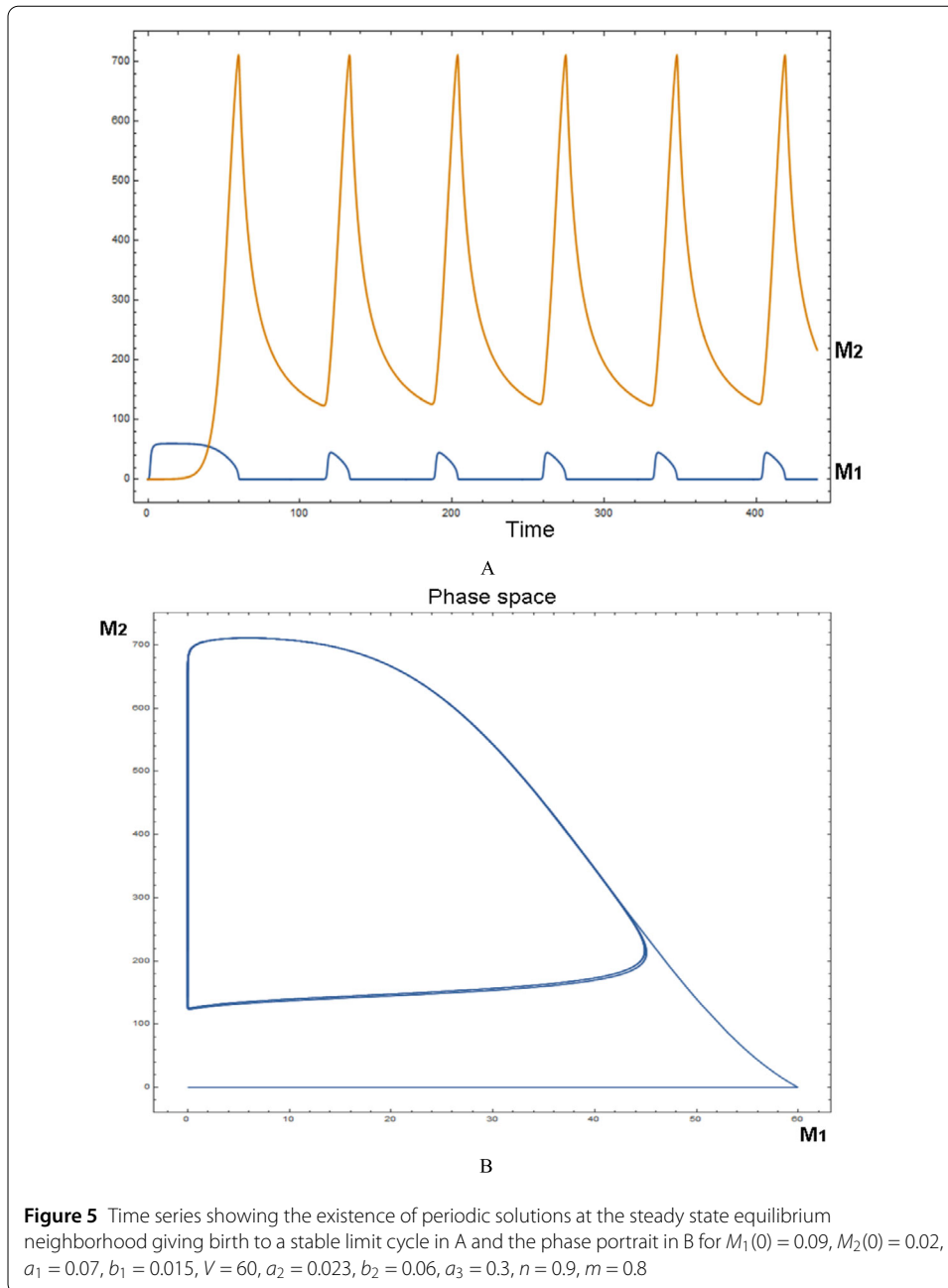


$$\begin{cases} \mu = (O + R)/2, \\ \omega = \pm\sqrt{(O + R)^2/4 - (O + R)/2 + OR - PQ}. \end{cases}$$

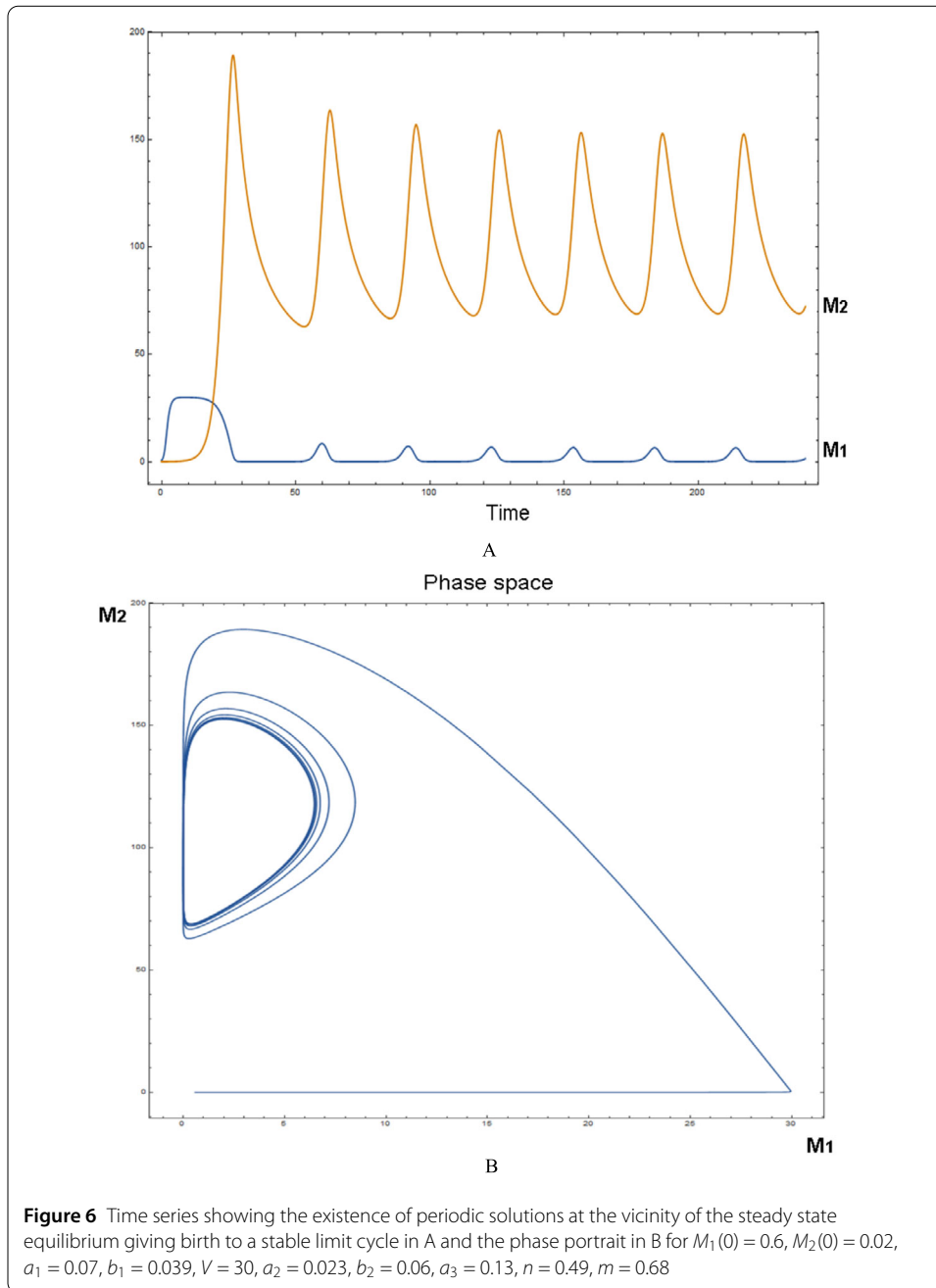
If $\mu = 0$, then a Hopf bifurcation occurs at (M_1^*, M_2^*) and all solution curves lie on $\omega = \pm\sqrt{OR - PQ}$ as far as $OR > PQ$. If $\mu \neq 0$, then at (M_1^*, M_2^*) neighborhood solution curves are spiraling inward or outward depending on μ sign.

5 Numerical results

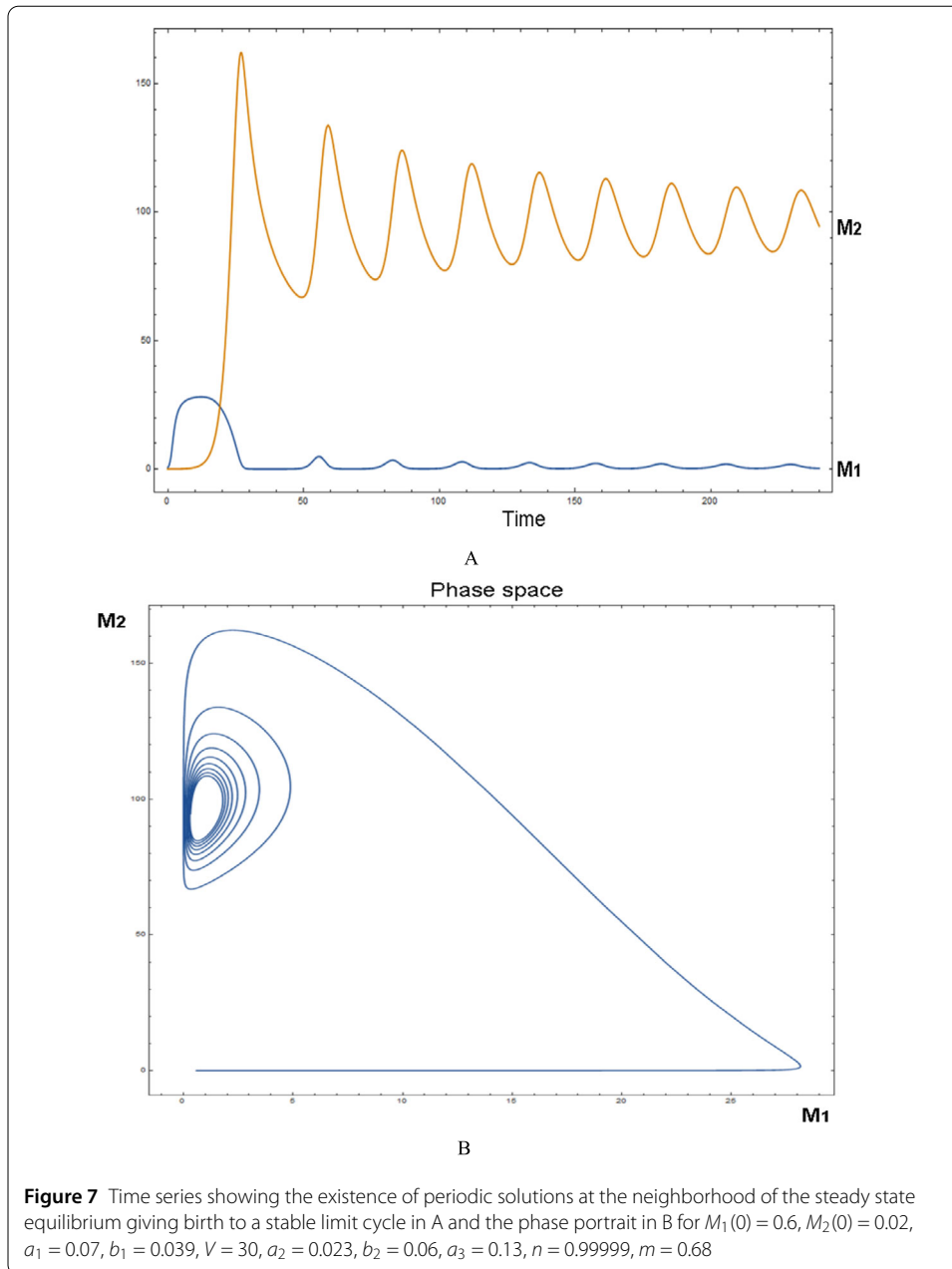
In this section, to test the proposed model predictability and validate the theoretical hypothesis, we carried out computer simulation (Figs. 3, 4, 5, 6, 7) and used data collected from the Chinese social network media Weibo (Figs. 8, 9, 10). Several situations of interac-



tion were considered. In all the scenarios, model parameters are constant. We computed M_1 and M_2 intrinsic growth factors respectively $a_1 = 0.03, b_1 = 0.9$ as per capita increase of the number of views per unit time (here per day, after rescaling the data for practical purpose). Computing $a_2, b_2,$ and a_3 is more challenging using the data at hand, a_2 being the effect M_2 has on M_1 , modeling M_1 per capita decrease in the number of views. b_2 is the positive feedback resulting from this interaction, while a_3 captures relative speed of increase in the number of views per unit time for M_2 . This implies that M_2 needs more time to benefit from positive feedback at high M_1 density. We varied initial conditions, interaction coefficients, system carrying capacity, and control parameters m and n to test system sensitivity to small perturbations and explore the interaction outcome.



1—Fig. 3 displays the dynamic of interaction when system is stable and there is peaceful coexistence for a given set of parameters value. Benefiting from a larger audience and a more reliable publisher, namely the authority, M_2 gets more views and stays attractive for a longer period of time. This validates the fact that releasing authoritative information containing the truth at a specific time is important to reduce the negative effect of persistent rumor or fake news. Control parameters m and n have significant impact on system dynamic in respect to per capita growth rate or the number of views per unit time. Adjusting these control parameters by improving exposition and stimulating readers' interest using marketing tools and techniques may result in enhancing the attractiveness of respective messages and stabilizing the system. As portrayed in Fig. 4, when we vary M_2 harvesting



coefficient significantly, the system exhibits rich dynamical behavior. The existence of periodic orbits and stable limit cycle at the vicinity of the unique positive equilibrium point, as illustrated in Figs. 5, 6, and 7, is interesting from system control perspective [25, 26].

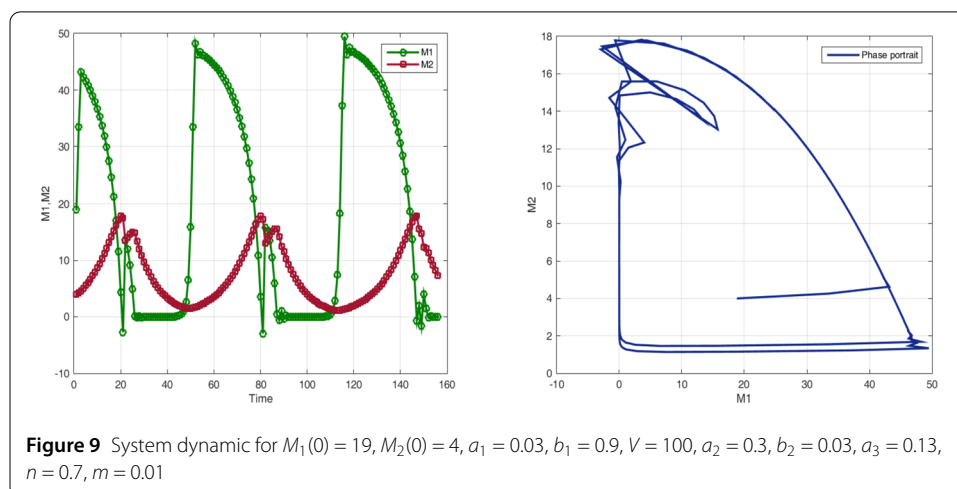
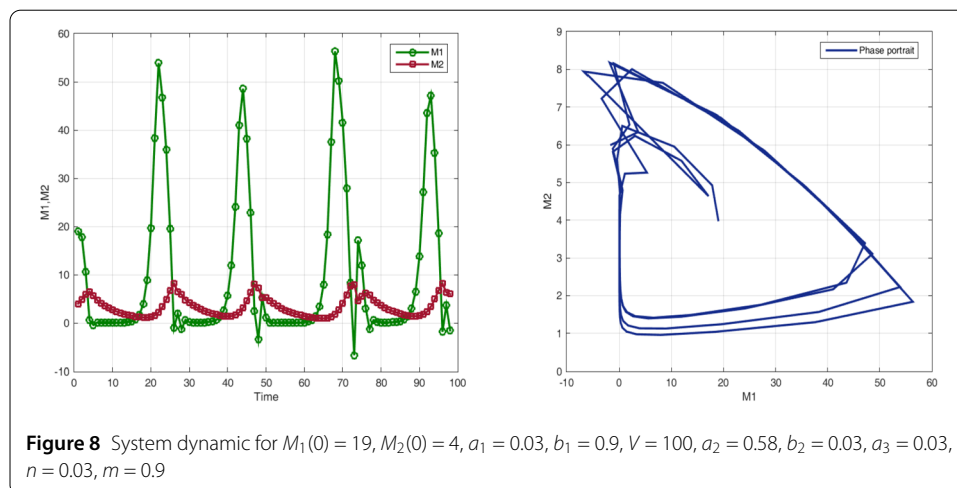
As interacting messages have strong correlation due to resources limitation, varying m and n will result in affecting significantly the amplitude of oscillations and directly the limit cycle at the vicinity of the steady state equilibrium. Adjusting these parameters may end up in optimizing resources allocation in a closed environment when competition is intensive to maintain system stability, as portrayed in Figs. 6 and 7.

Readers' interest for a subject will drop when there are more choices as competition will intensify. To reach a larger number of views, choosing trusted and reliable publishers is a

key in controlling information propagation among social networks targeted community or reducing propagating rumors negative effects on human mind and social wellbeing.

To support the decision in promoting broadcasted authoritative information and reduce the negative effect of rumor, decision makers need to analyze targeted community’s social ties, network structure and to release the curative content at the right time. The key control parameters m and n will be difficult to determine scientifically with accuracy, as they are related to users’ behavior which is stochastic in nature.

2—By varying control parameters m and n , interaction coefficient value and rescaling population size to 100, we obtained feasible results illustrated in Figs. 8, 9, and 10. A stable coexistence between the current rumor and the related authoritative information is shown. After the release of M_2 via the authority, the trending M_1 containing harmful contents shrinks at relative speed as more and more users enter in contact with M_2 as displayed in Fig. 8. By choosing $a_3 = 0.13$, $n = 0.7$, $m = 0.01$, we gave M_2 more time to assimilate captured resources and benefit from interaction, here attracting more users, as shown in Fig. 9. When the authoritative information is relatively attractive to the targeted community, the amplitude of oscillations is significantly affected.



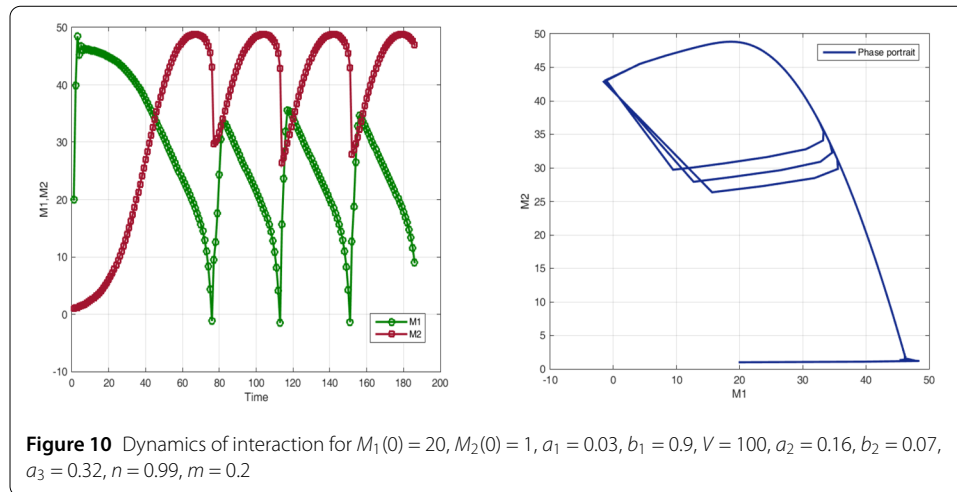


Figure 10 illustrates an ideal scenario for $a_2 = 0.16$, $b_2 = 0.07$, $a_3 = 0.32$, $n = 0.99$, $m = 0.2$, where the authoritative information overpowered the persistent rumor M_1 , resulting in less and less people propagating the latter. However, even when the majority of people are reading and propagating M_2 , there are still users who continue to be interested in M_1 , which is consistent with human mind and people inclination to experiment themselves what they hear about.

6 Conclusion

In this paper, to model the interaction effect of two messages traveling through social networks sharing the same interest for readers, we proposed a two-species logistic interactive model with Holling type functional response and maturation parameters for both interacting species. We considered respective attractiveness and thresholds for each message in respect to logistic growth and control parameters. We showed that controlling a strategic node or a publisher with highest reliability has a direct influence on system stability and resources availability for covering a larger audience in the targeted community. By applying stability theory and studying the system qualitatively, we found in numerical results that the system exhibited rich dynamical behavior, interaction dynamics was predictable, and the system could be stable for a given set of parameters value. Both species' dynamics are submitted to initial conditions, resources availability, marketing strategy, and publisher reliability through respective control parameters. From the field data at hand, we showed that maturation parameters and assimilation coefficient have significant impact on the steady state equilibrium dynamics, as the amplitude of oscillations changes when we vary respective parameters, shaping the system's asymptotic and global behavior.

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We declare that no founder has influenced the design, the analysis, and the interpretation of data of the work presented in this article.

Availability of data and materials

Data and codes generated and used in this study are available from the corresponding author upon request.

Competing interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Authors' contributions

YZ, FL, and YHK designed experiments; WH, YZ, and YHK carried out experiments and validated experimental results. FL and WH prepared Figs. 1–10; YHK and FL interpreted experimental results; YHK wrote the manuscript. All authors read and approved the final manuscript.

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