The evolutionary game analysis of incentive mechanism for crowd sensing of public environment

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Abstract. The public environment perception model regards people as a “data perceptron” and a human-centred participatory perception model. The enthusiasm and initiative of public participation will directly determine the effective operation of the model. This paper aims to understand how to stimulate public participation in data sensibility in public environment perception and establish an effective incentive mechanism. Based on the evolutionary game theory, a public environment perception evolutionary game model is established. The game selection between the data subject and the perceived participants is analysed. The group strategy selection and influencing factors of establishing effective incentive mechanism are studied. According to the replication dynamic equation, the behaviour evolution law and evolutionary stability strategy of public environmental group intelligence perception are obtained. The research results show that data users increase the proportion of investment in participants' incentive strategies, which will motivate participants to share more data and thus help them to evolve to the desired results. Encouraging participants to actively share data is necessary to reduce participants' participation costs, which requires data users to select target groups to participate in perceived tasks, and to select people who are more convenient to provide data; the data user's incentives should be sufficient to offset the participant's participation cost. The data user should ensure that both the quantity and quality of the public participation in the perceived task are optimal when the data user minimizes the payment.

1. Introduction

In recent years, with the frequent regional and multi-element ecological environment problems, after a long period of accumulation, superposition and spread, a series of complex ecological and environmental problems such as haze, global warming and sandstorms are intensively and seriously threatening people's normal production, life, physical and mental health. People have digitally recorded individual feelings toward environment and the influences through web platforms such as Weibo and WeChat. Public concern about the quality of the ecological environment, concern for environment protection, and participation in environment protection are unprecedentedly high. As a dynamic subject in the ecological environment, the public's accurate environmental perception is of great significance for indirectly reflecting regional environment quality, expressing public environmental demands, actively responding to government environmental policies, and establishing correct environment public opinion guidance.
John R. Gold[1] and K.P. Burnett[2] proposed a theory framework for the process of environment perception. Domestic scholars have carried out a lot of theoretical and empirical studies on perception such as environment perception mechanism[3], water environmental risk perception[4], climate change perception[5], environmental pollution perception[6], glacier change perception[7], meteorological disaster perception[8], public environmental perception environmental awareness[1]. Existing research of environment perception mainly collects public perception data through questionnaires, interviews and third-party observations, and uses statistical induction and cognitive models to study public environment perception rules and behaviours. Common sense[9] monitors the status of SO$_2$, CO, etc. through handheld air quality sensing devices. Sensor Map[10] establishes a network to monitor urban air quality through an air quality sensor equipped on the user's car; Creek Watch[11] is an application that collects water quality near people's rivers, including river flow, flow rate, and surrounding garbage status, then analyses and organises the data and shares it; PEIR[12], an application of environmental impact, analyses individual behaviours; Wang et al.[13] monitored the carbon monoxide concentration of air by installing a carbon monoxide sensor on campus. Aiming at the problems in the above literature research, this paper proposes a public environmental group intelligence perception model based on real-time submission of ecological environment by mobile terminals.

2. Public environmental group intelligence perception model and incentive mechanism

The public environment perception model is to use humans as “data perceptions”, based on the mobile devices (such as mobile phones, smart bracelets) that users carry with them, and actively submit the individual's perception information of objective environmental quality to form public objective data collection model for environmental quality-aware big data sets. Such data information includes both physical environment data reflecting the objective environmental quality and psychological environment data forming an impression in the individual's mind. By using large data sets formed by public context-aware models, we can use big data analytics to explore the interaction between individuals and the environment in order to achieve the purpose of identifying public behaviour, at the same time, this is a new model and new method to study the relationship between human and natural environment in the context of the application of big data and wireless sensing technology.

The public environment perception model is human-centred participatory perception. The biggest difference from opportunity perception is that the data in perceptual perception is uploaded by the user's unconscious perception, and the perceived participation requires the conscious and active participation of the person. Participation in the perception process and perceived data reliability play a decisive role in perceived outcomes. Simultaneously, in the public environment perception model, the public is both a participant in the data and a user of the data. As perceived participants, their own costs are considered while considering their privacy protection and deciding whether they are involved in data perception. As a data user, you need to get more high-quality data at a relatively low cost. In the actual operation process of the sensing system, there is a problem that the user participation is not high, that is, the number of participants and the data quality are not high[14]. Therefore, establishing an effective incentive mechanism to stimulate users to participate in the enthusiasm and initiative of submitting data is the key to the effective operation of the public environmental group perception model.

3. Model basic assumptions and construction

In the operation of the public environment perception system, perceived participants exhibit characteristics of individual rationality, uncertainty, selfishness, dishonesty and so on, because these characteristics make the participants have positive and non-active sharing of data. For data users who declare tasks, it is necessary to comprehensively consider the characteristics of user, and develop reasonable incentive mechanisms to encourage the participation of sensing devices to participate in sensing tasks and provide data, so as to maximize the utility of data users and participants. From the perspective of data acquisition and use, the interest groups of knowledge perception involving public
environmental groups are two groups: perceived data participants and data users. In the process of data perception, the perceptual data participant selects the strategy to decide whether to actively submit the perceptual data and data user selection strategy determines whether to provide rewards for perceived data participants. The following parameter settings and basic assumptions are given to the public context-aware system, as shown in Table 1.

| Definition                                                                 | symbol |
|---------------------------------------------------------------------------|--------|
| Data users receive income when participants actively participate           | $W_1$  |
| Data users gains when participants are not actively involved               | $W_2$  |
| Perceived participants' choice of revenue when actively sharing data       | $E_1$  |
| Perceived participants' choices when not actively sharing data             | $E_2$  |
| Total incentive costs for data user plans                                 | $P_1$  |
| Perceived participants' choice of actively sharing data to earn incentives as a percentage of incentive costs | $\theta$ |
| Perceived participants actively share data costs                          | $P_2$  |
| Loss caused by non-incentives by data users when participants actively participate | $C_1$  |
| Loss caused by non-incentives by data users when participants are not actively involved | $C_2$  |

Hypothesis 1: The data user obtains the comprehensive economic benefit marked as $W_1$, when the participant chooses to actively participate; the data user obtains the comprehensive economic benefit marked as $W_2$ when he perceives that the participant chooses not to actively participate. Due to comprehensive consideration, if the perceived participants choose to actively provide data for the user to study, in this case, the data user's income is significantly greater than when the perceived participant does not actively provide data, that is $W_1 > W_2$.

Hypothesis 2: When perceived participants choose to actively share data, the overall economic benefits they receive are $E_1$; when the perceived participants choose not to actively share the data, the comprehensive economic benefits they receive are $E_2$. When the perceived participants choose to share the data for the user to study or analyse, it contributes to the social ecological construction and the living environment, and also obtains a good feedback on the overall income of the user. In this case, the obtained overall benefits are also greater than when the data is not actively shared, that is $E_1 > E_2$.

Hypothesis 3: The cost of using mobile devices when perceiving participants to actively participate in sharing data, downloading the APP and submits the data that would be using the data traffic, consuming the storage space of the mobile phone, the economic cost of the participants at this time plus the time cost of consumption is $P_2$. When participants actively share data and data users take no incentives, it will affect the number of perceived participants and the quality of the shared data, resulting in losses, $C_2$, when data users perceive participants not actively sharing data, loss caused by non-incentives is set to $C_2$, at this time $C_1 > C_2$.

According to the comprehensive analysis of the public environmental group intelligence perception incentive mechanism and the setting of the above parameters, the game payment matrix for data users and perceived participants is obtained, as shown in Table 2.
4. System Stability Strategy Analysis

In the process of public environment perception system evolution, different groups will choose different strategies. Set the probability of data users choosing incentive is \( x \) \( (0 < x < 1) \), choose not to motivate the probability of \( 1-x \); The probability that participants choose to actively share data is \( y \) \( (0 < y < 1) \) and the probability that they choose not to actively share data is \( 1-y \).

The expected benefit of a data user when adopting an incentive strategy is:

\[
Z_{11} = y(W_1 - \theta P_1) + (1-y)[W_2 - (1-\theta)P_1] \quad (1)
\]

The expected benefit when the data user chooses not to motivate the strategy is:

\[
Z_{12} = y(W_1 - C_1) + (1-y)(W_2 - C_1) \quad (2)
\]

The average revenue of data users is:

\[
\bar{Z}_1 = xZ_{11} + (1-x)Z_{12} \quad (3)
\]

The expected benefits when perceiving participants to actively share data is:

\[
Z_{21} = x(E_1 + \theta P_1 - P_2) + (1-x)(E_1 - P_2) \quad (4)
\]

The expected benefits when perceiving participants choosing not to actively share data is:

\[
Z_{22} = x[E_2 + (1-\theta)P_1] + (1-x)E_2 \quad (5)
\]

The average benefit of perceived participants is:

\[
\bar{Z}_2 = yZ_{21} + (1-y)Z_{22} \quad (6)
\]

The dynamic analysis of the replication of the two types of group games is performed, and the dynamic equation of the data user is:

\[
F(x) = \frac{dx}{dt} = x(Z_{11} - \bar{Z}_1) = x(1-x)(Z_{11} - Z_{12}) = x(1-x)[C_2 - P_1 + y(C_1 - C_2)] \quad (7)
\]

The dynamic equation of the perceptual participant’s replication is:

\[
F(y) = \frac{dy}{dt} = y(Z_{21} - \bar{Z}_2) = y(1-y)(Z_{21} - Z_{22}) = y(1-y)[(2\theta P_1 - P_1)x + E_1 - E_2 - P_2] \quad (8)
\]

If \( F(x) = 0 \), get: \( x_1 = 0 \), \( x_2 = 1 \), \( \hat{y} = \frac{(1-\theta)P_1 - C_2}{(1-2\theta)P_1 + C_1 - C_2} \quad (0 < \hat{y} < 1) \quad (9) \)

If \( F(y) = 0 \), get: \( y_1 = 0 \), \( y_2 = 1 \), \( \hat{x} = \frac{E_2 + P_2 - E_1}{(2\theta - 1)P_1} \quad (0 < \hat{x} < 1) \quad (10) \)
The five equilibrium points calculated by the above equations are: \( F_1(0,0), F_2(0,1), F_3(1,0), F_4(1,1), F_5(\hat{x}, \hat{y}) \).

If the equilibrium point of the evolutionary game is satisfied \( \text{Det}(J) > 0 \) and \( \text{Tr}(J) < 0 \), the equilibrium point is an evolutionary stability strategy, and the corresponding equilibrium point is a stable point. The model in this paper assumes that the parameters involved are greater than 0, according to the decision condition of the system ESS, five equilibrium points are analysed through the evolutionary game of data users and perceived participants, just discuss these two conditions when \( (1-\theta)P_l < C_2 < C_1 < \theta P_l \) and \( C_2 < (1-\theta)P_l < \theta P_l < C_1 \), the calculation results are shown in the following table: If \( (1-\theta)P_l < C_2 < C_1 < \theta P_l \):

| Balance point | \( \text{Det}(J) \) | \( \text{Tr}(J) \) | Properties |
|---------------|-------------------|-----------------|------------|
| \( F_1(0,0) \) | -                 | -               | Saddle point |
| \( F_2(0,1) \) | -                 | -               | Saddle point |
| \( F_3(1,0) \) | -                 | -               | Saddle point |
| \( F_4(1,1) \) | -                 | -               | Saddle point |
| \( F_5(\hat{x}, \hat{y}) \) | + 0              |                 | Saddle point |

In this case, the final evolution result is not stable, and both the data user and the perceived participant groups are bounded and rational, finally they will find the most favourable choice. If the evolution of the system begins to perceive the participants to receive incentive rewards, but the data users are not motivated because the incentive costs are too large, which is likely to cause the perceived participants to lose trust in the data users, hence getting data will face failure. Therefore, this condition does not conform to the actual situation, and the second case is directly considered.

If \( C_2 < (1-\theta)P_l < \theta P_l < C_1 \):

| Balance point | \( \text{Det}(J) \) | \( \text{Tr}(J) \) | Properties |
|---------------|-------------------|-----------------|------------|
| \( F_1(0,0) \) | +                 | -               | Stable point |
| \( F_2(0,1) \) | +                 | +               | Unstable point |
| \( F_3(1,0) \) | +                 | +               | Unstable point |
| \( F_4(1,1) \) | +                 | -               | Stable point |
| \( F_5(\hat{x}, \hat{y}) \) | - 0              |                 | Saddle point |

It can be obtained \( F_2(0,1), F_3(1,0) \) is unstable, \( F_5(\hat{x}, \hat{y}) \) is saddle point, \( F_1(0,0), F_4(1,1) \) are the stable point, i.e. ESS, which responds to 2 cases, data users to take incentives, perceive participants to actively share data and data users not to take incentives, and perceive participants not to actively share data, respectively. From the analysis of the properties of the above 5 equilibrium points, the dynamic evolution phase diagram can be obtained:
Figure 1 depicts the dynamic process of evolutionary game between data users and perceived participants. By two unstable equilibrium points $F_1$, $F_2$ and saddle point $F_3$, the connected fold line is the critical line where the system converges to different states, in the upper right Q and H areas of the poly-lines, the system will gradually converge to two groups of incentives and active participation. In the M and N regions at the bottom left of the poly-lines, the system will gradually converge to two groups that are not motivated and not actively involved. Since the evolutionary game is a dynamic evolution process, the above two situations have the rationality of existence within a certain period of time.

5. Evolutionary Game Analysis and Discussion
In the process of the public environmental group perception game, the initial values of some parameters that constitute the income function of both sides of the game and their changes will cause the evolutionary system to converge to different equilibrium points. Therefore, the final evolution state of the result is determined by the initial state of the game. It can also be said that it is related to the size of QH and MN area. When the initial state of evolution begins in the Q and H regions, the system converges on the point of $F_d(1,1)$. For the ideal evolution result, it is hoped that the system will converge to the state of $F_4$ point, at this time, the Q and H regions will expand, and the $F_3$ point will tend to move to the lower left. The position of this point has a direct impact on the two regions. Therefore, changes in values of $P_1$, $\theta$, $P_2$, $C_1$ and $C_2$ will change the size of the two regions, which will affect the convergence result of the system. From the above analysis, it can be concluded that:

As the maximum incentive cost of data user plan, $P_1$ itself has little influence on the decision of both sides of the game. But $\theta$ is rewarded for choosing to actively share data as a participant. The proportion of the reward to the incentive cost has a direct impact on the decision-making of both parties. The data user increases the proportion of participants' incentives, the area of QH above the fold line expands correspondingly, and the probability of the system converging to $F_4$ point increases. Conversely, the probability of system convergence $F_3$ increases.

$P_2$ represents the cost of participation of data users. The system will gradually converge to $F_1$ when the perceived cost of participants who provide data is too high. It can be seen from the phase diagram that the position of saddle point $F_3$ will move up and MN area will increase. In this case, participants are likely to choose not to actively share data unless they are satisfied with the compensation and rewards they receive. As a data user, to encourage participants to actively share data, it is necessary to reduce the cost of participation.

$C_1$ and $C_2$ are losses caused by data users not taking incentive measures when participants actively participate in data sharing and do not actively participate in data sharing, respectively. As can be seen from the phase diagram of the system, when $C_1$ increases, QH area increases, and when $C_2$ increases, MN area increases. Therefore, when the participants do not actively share the data, the loss of the data user is relatively small. When the perceived value of data obtained by participants is insufficient to offset the input cost of data users, there is no reason for data users to adopt incentive measures at this time.
6. Conclusions

This paper proposes a public environment perception model, which analyses the key role of incentive mechanism in improving the enthusiasm of perceived participants for the process of public participation in perception tasks. Through the analysis of the evolutionary game model, it mainly analyses the necessity of the existence of incentive mechanism and the positive and non-positive situation of perceived participants. The evolution has two results that the participants actively share the data and the data provider adopts an incentive mechanism, and the perceived participants do not actively share the data and the data providers do not adopt the incentive mechanism. The final evolutionary convergence results are related to parameters such as $P_1$, $\theta$, $P_2$, $C_1$ and $C_2$. In the actual system operation, it is necessary to improve the enthusiasm of participants by increasing the incentive cost of data users, reducing the perceived cost of perceived participants and coordinating the interest relationship between participants and data users.

Game analysis shows that data users should take incentive measures to obtain effective data, enrich the incentive forms within the costing plan, and select the correct target population. At the same time, we must have a comprehensive technology to guarantee the accuracy and reliability of the data. For perceived participants, it is necessary to strengthen self-cultural literacy, have a correct concept of environmental protection, and be willing to share data while paying more attention to protecting privacy. The protection of the environment is a long-term and arduous task. Of course, the government and enterprises have great responsibilities, but everyone's awareness of environmental protection should be gradually improved, and they should work for the construction of beautiful environment together, so the overall benefits of society and individuals can have a greater increase. For the government, it is necessary to promote the convenience of data users to obtain data, supervise the safety and correctness of their data use, enhance the enthusiasm of public participation, and protect ecological environmental protection work.

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References

[1] Wikipedia S, TB/Biologie/Grundlagen. An introduction to behavioural geography[M]. Oxford University Press, 1980.
[2] Jacqueline Desbarats. Spatial choice and constraints on behavior[J]. Annals of the Association of American Geographers, 1983, 73(73):340-357.
[3] Rocha K, Pérez K, Rodríguezsanz M, et al. Perception of environmental problems and common mental disorders (CMD)[J]. Social Psychiatry and Psychiatric Epidemiology, 2012, 47(10):1675-1684.
[4] Zoellner J, Hill J L, Zynda K, et al. Environmental perceptions and objective walking trail audits inform a community-based participatory research walking intervention[J]. International Journal of Behavioral Nutrition and Physical Activity, 2012, 9(1):6.
[5] Medaniels T L, Axelrod L J, Cavanagh N S, et al. Perception of ecological risk to water environments[J]. Risk Analysis, 1997, 17(3):341-352.
[6] Bord R J, Fisher A, O'Connor R E. Public perceptions of global warming: United States and internation perspectives[J]. Climate Research, 1998, 11(1):75-84.
[7] Wardekker J A. Ethics and public perception of climate change: exploring the christian voices in the US public debate[J]. 2009, 19(4):512-521.
[8] TAN Lingzhi, MA Changfa. Farmers' Perceptions of Climate Change and Their Adapting Behaviors in Arid Region of China [J]. Bulletin of Soil and Water Conservation, 2014, 34(1):220-225.
[9] Reddy S, Parker A, Hyman J, et al. Image browsing, processing, and clustering for participatory sensing: lessons from a DietSense prototype[J]. Emnets '07 Proceedings of Workshop on Embedded Networked Sensors, 2007:13-17.

[10] Eisenman S B, Miluzzo E, Lane N D, et al. BikeNet: A mobile sensing system for cyclist experience mapping[J]. Acm Transactions on Sensor Networks, 2009, 6(1):6.

[11] Rai A, Chintalapudi K K, Padmanabhan V N, et al. Zee:zero-effort crowdsourcing for indoor localization[C]// 2012:293-304.

[12] Rana R K, Chou C T, Kanhere S S, et al. Ear-phone: an end-to-end participatory urban noise mapping system[C]// ACM/IEEE International Conference on Information Processing in Sensor Networks. ACM, 2010:105-116.

[13] Dutta P, Aoki P M, Kumar N, et al. Common Sense:participatory urban sensing using a network of handheld air quality monitors[C]// International Conference on Embedded Networked Sensor Systems, SENSYS 2009, Berkeley, California, Usa, November. DBLP, 2009:349-350.

[14] NAN Wenqian, Guo Bin, Chen Huihui, et al. A Cross-Space, Multi-Interaction-Based Dynamic Incentive Mechanism for Mobile Crowd Sensing [J]. Journal of computer, 2015, 38(12): 2412-2425.