Autonomy-oriented proximity mobile social network modeling in smart city for emergency rescue

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Abstract
Nearest neighbor mobile social network means that movers approaching in position communicate through their social sensors, which is called Proximity Mobile Social Network. Proximity Mobile Social Network can provide more social and business opportunities for users. To carry out disaster relief work in post-disaster environment, we need to collect incident information during the search process and report to the sink in time. Proximity Mobile Social Network provides flexible systems for emergency handling and disaster relief. Therefore, how to find a better data forwarding and routing strategy is the key problem of post-disaster rescue, and the research of user mobility model is the basis of the above problems. This article presents an Autonomy-Oriented Proximity Mobile Social Network modeling for emergency rescue in smart city, which simulates the network operating environment. First, we verify the performance of Autonomy-Oriented Proximity Mobile Social Network model in terms of self-organization, scale-free, aggregation, and community structure. Then, the rescue efficiency is discussed through the coverage of mobile sensors. Finally, performance of the routing strategy based on Autonomy-Oriented Proximity Mobile Social Network model is analyzed, and the effectiveness of the method is proved.

Keywords
Proximity mobile social network, social network of sensors, social network, mobility model, autonomy-oriented, emergency rescue

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Introduction
Nearest neighbor mobile social network means that movers approaching in position communicate through their social sensors, which is called the Proximity Mobile Social Network (PMSN). PMSN can provide more social and business opportunities for users. To carry out disaster relief work in post-disaster environment, we need to collect incident information during the search process and report to the disaster relief command center in time. PMSN provides flexible systems for emergency handling and disaster relief. Therefore, how to find a better data forwarding and routing strategy is the key problem of post-disaster rescue, and the research of user mobility model is the basis of the above problems.

The dynamic characteristics of network topology have a great influence on its performance. The perfect network topology mechanism can improve the efficiency of routing algorithm and media access control protocol, and support data fusion, time synchronization and target location. At the same time, the more perfect the topological mechanism of the network is, the more effective the routing strategy based on Autonomy-Oriented Proximity Mobile Social Network model is analyzed, and the effectiveness of the method is proved.

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the longer the life cycle that can operate normally. PMSN does not require any preexisting infrastructure to establish their communications. Therefore, they are also known as infrastructure-free networks. This is considered an advantage over traditional infrastructure such as mobile phone networks.

However, due to the highly random mobility of self-organizing users, PMSN topology changes dramatically over time, and may be highly dynamic, making maintaining communication links difficult. Therefore, if the dynamic characteristics of PMSN topology can be mastered, efficient topology control algorithms can be designed to optimize network performance so that the network can provide reliable services continuously and steadily. It is expensive and difficult to study the dynamic topology of PMSN because of large-scale field trials. Therefore, researchers use various mobile network models to do simulation research. Some allow users to move randomly, while others use active data from an existing database to simulate a move.

In order to simulate mobile network applications, many mobile network models have been proposed. However, the existing models do not consider self-organization of human social relations on the model. We believe that in the real world, social sensors are usually carried or controlled by self-organizing users, so the way of movers in the network potentially reflects the characteristics of human behavior. Especially in the urban environment, due to the increase of network scale, the impact of self-organizing users cluster characteristics on network performance is also increasing. Therefore, we propose a social mobile network model using a multi-agent complex network with neighborhood mobile sensors, namely, the Autonomy-Oriented Proximity Mobile Social Network (AOPMSN).

The following structure is organized in this article: section “Related work,” based on the viewpoint of multi-agent mobile network model, compares the related mobile network models. In section “AOPMSN modeling,” based on PMSN, a scenario of post-disaster rescue using social mode is presented, and an autonomous mobile social network model is proposed and constructed. In section “Simulation of AOPMSN model,” the performance of the routing strategy based on AOPMSN model is analyzed, and the effectiveness of the method is proved by simulation. Finally, in section “Conclusion,” our conclusions are given.

**Related work**

Computer network, whether fixed network or mobile network, will be affected by human social relations. For example, WWW sites will have different age, occupation, interest groups, and mobile phone call relationship is a direct reflection of human social relations. PMSN is also a kind of computer network. Because the holders of mobile devices are human beings, the mobile characteristics and connection decision behaviors of devices must be affected by human behavior and social relations, so its communication connection is at least not completely random.

The mobile network can be modeled as a mobile multi-agent network model. From the point of view of complex network, we divide it into a stochastic mobile multi-agent network model and a social mobile multi-agent network model.

**Stochastic mobile multi-agent network model**

In the random mobile network model, the agents move randomly without direction. Specifically, the agent randomly chooses its destination, moving speed, and random moving direction. Typical mobile agent network models include RWPM (random way point model), RW (random walk model), and RD (random direction model). These mobile agents’ network models mimic the behavior of users in the simplest way possible. But at the same time, there is a lack of precise and specific description of the characteristics of users in the actual movement process, such as motion area, time, and space status. As a matter of fact, users have different patterns of motion in different environments. Users move in a regular manner, and are not completely random.

The research of mobile multi-agent network model is the premise and foundation of PMSN routing strategy design and performance evaluation. It will help us better understand the network performance and possible problems, thus promoting the specific implementation and performance improvement of the network. In the early stage of link stability research, the RWPM is used as the mobile model. The degree distribution of mobile models based on RW and RWPM models emerges from Poisson’s distribution. In previous studies, Poisson’s distribution has been widely used to quantify human activity model and analyze the statistical law of behavior events per unit time, such as traffic configuration of business center by Reynolds, inventory management by Greene, and estimation of the number of busy calls by Anderson.

At present, many behavioral statistical properties cannot be described by Poisson’s distribution. Since Poisson’s distribution describes the occurrence of random events in a steady state, this model requires that human behavioral characteristics be uniformly distributed, but human behavior has been shown to be explosive or stationary for a long time. Poisson’s distribution cannot be used to explain this behavioral characteristic. With the defects of the RWPM constantly emerging, other mobile network models which are closer to the real agent mobility have been gradually applied.
Social mobile multi-agent network model

Through scientific research on real data sets, academia has confirmed that human mobile behavior has regularity.9,13 This regularity not only refers to the regularity of individual mobile behavior in the network, but also includes the mobility law of groups in the network.

Barabasi’s paper14 questioned the theory that the human behavior model is Poisson’s distribution. By analyzing the statistical characteristics of users sending and receiving email, it is proposed that the interval between users receiving and sending email for two consecutive times meets the power law distribution, it is pointed out that the degree distribution of agents in social networks is a new viewpoint of power law distribution. Song’s user mobile model discovered that according to the inherent law of human mobility behavior,15 human mobility has an average potential predictability of 93%. Based on Song’s model, a social sensors’ network is proposed and simulated.16

Some recent work in modeling human movement is based on network science to represent social relationships as the primary driver of individual movement. Social relations are described as a multi-agent network, in which agents represent mobile users and links represent the relationship between mobile users. Social network refers to the collection of stable social relations formed by interaction between social groups (individuals or groups). The main body of PMSN is wireless devices (mobile phone, pad, etc.). Therefore, the mobility of agents is affected by human social behavior. There must be some stable social relationship between agents. The introduction of social network theory into PMSN enables the model to have the characteristics of PMSN and social network.

In traditional random networks, although the connections are set randomly, the number of connections of most agents will be roughly the same, that is, Poisson’s distribution of agent connections. It has been proved that the social network model is not a random network, but a complex network. As a typical multi-agent complex network, social networks are characterized by weak connections, scale-free, and high aggregation. Weak link advantages accelerate the diffusion. The scale-free characteristic facilitates propagation; high clustering makes communication family or community clustered.

Previous studies have found that homogeneity, resource dependence, community attachment, and new location exploration have formed four kinds of mechanisms of mobile behavior network in human society. Based on the above mechanism, this article studies the feature emergence of social network mobile model.

First, homogeneity describes the tendency of actors to search and select actors similar to themselves to establish connections.17 Homogeneity means that connected individuals in social networks tend to be “similar,” that is, the similarity and compatibility between individuals in social networks have an important impact on whether they form edges. Based on homogeneity, an agent selects an agent that has similar features with the agent’s. The formation process of some typical networks is characterized by the quantitative expression of homogeneity phenomenon “Distant relatives are not as good as close neighbors” reflects the impact of spatial distance on interpersonal communication.

Second, the resource dependence mechanism affects the mobile behavior network of human society. According to the resource dependence theory, the more resources an agent has, the more likely it is to attract other agents. In terms of resource dependence effect, an individual is associated with another individual who has more resources than himself.18

Third, community preferred attachment means that agents with the same social characteristics have a high probability of meeting, that is, agents in the community meet frequently, which is a common phenomenon in society. For example, people working in the same company meet more frequently than people working in different companies. The same examples include schools, houses, and so on. This attribute is determined by the community characteristics of human activities. Therefore, using the idea of community to forward messages can improve the delivery efficiency of message packages.

Finally, the social network mobility model is inseparable from the agent’s exploration of new locations. For example, rescuers need to search everywhere.

AOPMSN modeling

The problem

The actual scenario of post-disaster rescue is conceived. In the post-disaster rescue PMSN, it is assumed that the main participants in the rescue work can be divided into two categories: static agent and mobile agent. One is a fixed position emergency communication rescue vehicle and an emergency command and dispatch center (sink), which can be regarded as a static agent. As shown in Figure 1, there are four emergency communication rescue vehicles, the flag in the middle represents the sink agent, the humanoid agent represents the rescuer, and the round face agent represents the rescued.

N autonomous agents are distributed in plane according to some distribution law. Agents can be self-rescuers, community managers, volunteers, and search and rescue personnel. Search and rescue personnel are equipped with wearable devices that can carry out wireless communications. They can move search and rescue in the affected area.
The model

Autonomous computing starts from the law of self-organization and emergence in nature, and gets inspiration from the operation and structure of complex systems such as biology and society. It designs computing systems, depicts the behavior of complex systems, and solves complex computing problems. Autonomous computing is used to describe the complex dynamic process of PMSN system.

This article proposes a smart city emergency rescue neighborhood mobile social network model based on self-organizing computing.19,20 An AOPMSN system mainly includes self-organizing multi-agent network, the running environment of autonomous agents, and the goal of self-organizing system.

**Definition 1.** $\text{MAN} = \langle A, L \rangle$ is a PMSN where the symbol MAN is used to represent multi-agent networks, $A = \{A_1, \ldots, A_P\}$, and $L = \{\langle A_i, A_j \rangle | 1 \leq i, j \leq P, i \neq j \}$, where $A$ is the set of agents and $L$ represents the set of dynamic links between agents.

**Definition 2.** Environment $E = \{e_{s1}, \ldots, e_{sK}\}$, where each corresponds to a static or dynamic attribute, and $K$ is the number of attributes.

$E$ is the environment where autonomous mobile users and autonomous mobile terminals reside. At each moment, $E$ describes the current state of the environment.

**Definition 3.** An AOPMSN system is three tuples $\langle \text{MAN}, E, F_{obj} \rangle$. The symbol MAN is used to represent multi-agent networks, and $E$ is the environment in which man resides, $F_{obj}$ is the objective function of self-organizing system, usually the non-linear function of autonomous agent state.

**Definition 4.** The neighborhood of autonomous agent $A$ is a group of autonomous agents $N_A = \{N_{A1}, \ldots, N_{AL}\}$. The relationship between each neighbor $N_{AK}$ and autonomous agent $A$ satisfies the dependency constraint, $N_{Ai} = \{Ai | d(Ai, Aj) \leq \text{sensor radius}, i \neq j \}$.

**Definition 5.** The state set of autonomous agent $A$ is written as $AS = \{AS_1, \ldots, AS_N\}$, where the state $AS_i$ is an attribute of autonomous agent $A$. Metrics used to measure opportunistic networks based on human vectors usually include spatial properties, temporal properties, and social properties.

Spatial attributes describe the movement behavior of users in physical space. In AOPMSN, the research on metrics based on spatial attributes is mainly: length of jump, sum of frequencies, and flight length. Time attribute describes the characteristics of people’s moving behavior over time. The measurement based on time attribute has the following indicators: pause time/wait time, contact time, and inter contact time. Social attributes describe the interaction between users. The metrics based on social attributes mainly include the following aspects: contact frequency, social similarity, and community.

**Definition 6.** Autonomous agent $A$ can have a set of goals, which are written as $AG = \{ag_1, \ldots, ag_N\}$. Each goal $ag_i$ is to obtain a state, which satisfies the evaluation function $f$ to obtain a predefined value. In PMSN, each target $g_{i}$ can be an autonomous agent $A$ aware of the event. It is defined as follows

$$f(\text{events}, N_{Ai}) = \begin{cases} \text{true, event } \in N_{Ai} \\ \text{false, else} \end{cases} \quad (1)$$

**Definition 7.** The behavior set of autonomous agent $A$ is written as $AB = \{ab_1, \ldots, ab_N\}$, where $ab_i$ is the intelligent behavior of autonomous agent $A$.

**Definition 8.** The rule set of autonomous agent $A$ is written as $AR = \{ar_1, \ldots, ar_N\}$, where $ar_i$ is the behavior rule of autonomous agent $A$.

The computation process of autonomic computing intelligence is a non-linear process, and self-organizing emergence provides a solution for system solving computation. The convergence of autonomous computational intelligence requires that the non-linear solution
process of complex systems tends to be saturated and stable near a certain system solution under the action of positive/negative feedback mechanism.

**Definition 9.** In an AOPMSN, $F_{obj}$ is the objective function of the state of the autonomous agents. The target feature of search and rescue is that the search and rescue personnel find all the rescued individuals in the shortest possible time. The system objective function $F_{obj}$ defined as

$$\text{Min} \sum_{i=1}^{m} A_i(t)$$  \hspace{1cm} (2)

**Construction of AOPMSN**

So far, the topological model of complex social networks is mainly proposed to describe the topological structure of complex social networks. The connection between social network agents is mainly constructed by priority connection. Priority connection is rough to describe the joining process of new agents, because the newly added agent will all connect to the same agent. Therefore, in order to establish a more realistic network model with social network topology characteristics, we need to consider more perfect joining rules. Based on this problem, a self-organizing model of information transmission is proposed.

Specifically, we envisage a practical PMSN application scenario—post-disaster rescue scenario. Each agent of the network can interact with the surrounding agents within a certain communication radius. Initially, the connection of agents is random. Based on the principles of homogeneity, resource dependence, community priority attachment, and new location exploration, individuals will gradually carry out self-organizing interaction selectively according to the address, interest, and “hot” degree of their holders. After a period of time, the mobility of network agents decreases, and its distribution is relatively stable. When the network evolves to a certain extent, it will show non-uniformity, and some macro topological characteristics will emerge in the network.

Based on homogeneity, it is mainly an experience to search locally with a certain $P_1$ probability to establish contact with individuals who are physically close to themselves, such as the same family members, close neighbors, colleagues in the same company, classmates in the same school, and so on. Based on the principle of resource dependence, individuals will exchange information with individuals who have more resources in their community (such as community managers and volunteers) with a $P_2$ probability. Rescuers who enter a network are deeply inclined to connect with those with high agents. Based on the principle of community priority attachment, the main reason is that individual agents will concentrate in a specific area with a $P_3$ probability. People belonging to the same community have a high probability of meeting each other and will meet regularly. In other cases, rescuers need to constantly explore new locations.

According to the actual situation, four probability parameters can be defined: homogeneity, resource dependence (RDT), community priority attachment, and new location exploration. The construction model can be reflected by the definition of connection probability $p$ between agents. Since there are four network mechanisms to be modeled in this model, the probability of rescuers searching for new places in the community is equal to 100 minus the probability of resource dependence effect, the probability of homogeneity effect, and the probability of community priority dependence.

According to the above rules, the whole system is refreshed in a synchronous manner. The following is the simulation pseudo code algorithm of our self-organizing network model.

**Initialize the system;**
**For each step**
  **For each site**
    Agent interact neighbor on homophily with $[\text{Resource} = \text{R}]$ according to $ar_1$;
    Agent interact neighbor on RDT with $[\text{Resource} > \text{R}]$ according to $ar_2$;
    Agent interact neighbor on community priority according to $ar_3$;
    Agent interact neighbor on new location exploration according to $ar_4$;
    Agent set destination on probability according to $ar_5$;
    Agent set-stay-time on arrive destination according to $ar_6$;
    Agent set speed-min and speed-limit according to $ar_7$;
  **End**
**End**

Under the given configuration, the simulation starts to run, and rescue agents move and explore in a self-organizing manner according to specific rules in the smart city community, and a dynamic rescue scenario emerges. When the autonomous agent detects the event, it begins to propagate to other agents. When all event message reaches the sink agent, the simulation stops.

**Simulation of AOPMSN model**

**Simulation scenario and process**

This section presents a model for simulating autonomous neighborhood mobile social network. Based on the NETLOGO multi-agent complex network...
modeling environment, we implemented a PMSN simulator. The simulator supports AOPMSN modeling in smart city for emergency rescue.

Considering the smart city community scenario, rescuers carry sensors to form an AOPMSN. The communication type among sensors is peer-to-peer. We provide the average of 10 runs for each approach. The parameters in the simulator are shown in Table 1. The number of mobile agents \( n \); operation area \( A \) (\( m^2 \)); communication range of sensor \( r \) (m); agents moving speed \( v \) (m/s).

In this AOPMSN environment, there are two types of autonomous agents deployed: emergency communication rescue vehicle agents with initial static sensor interfaces deployed in four fixed locations, and mobile rescue agents carrying social sensors are randomly distributed uniformly. After the model runs, the mobile rescue agent moves at a constant speed. The forwarding protocol used by autonomous agents to propagate messages is the epidemic protocol.\(^{22}\)

Simulation results of AOPMSN

Verification of AOPMSN. In this section, we will verify that the model we proposed and constructed has the characteristics of social network.

Self-organized emergence of connected patterns. When studying the stability of complex networks, we can use the average shortest length (API) of the network to evaluate and analyze. Considering that PMSN is a dynamic network, agents are often disconnected, and API cannot be used to measure in an unconnected network, our experiment uses the metric of connectivity. One of the evaluation metrics which has been taken into account is the self-organizing emergence over time of the biggest connected component. The size of the biggest component present in the network has been defined as being the value of connectivity of the network, which defines the probability that if we randomly pick two agents of the network there exists a path between them through which they are capable of communicating with each other. Connectivity has a strong meaning for the network we obtain because what it basically means is how many agent is the giant component made of, and therefore, how many agents are at a given time reachable in terms of communication. Given this definition of connectivity this is the metric of the network we obtain which we most care and pursue to maximize (the greater this value is, the better the connectivity is).

Running the model, the agent appears randomly in the interface. Figure 2 shows that the agent presents the dynamics in the physical space in the experiment, indicating some emergent behaviors in the physical space. When \( n = 30 \), the number of autonomous agents is small, and the connection ability is low. When \( n = 200 \), the number of agents is large, so the connectivity is high. It can be seen from Figure 2 that by simulating the behavior of the subject, the connectivity patterns emerging from the self-organization of different groups can be observed (Figure 2).

Degree distribution of network agents. The first metric which is the degree distribution let us to know to what law the degree distribution obeys. Degree centrality describes the relevant characteristics of individuals in the network topology. Due to the different nature of the real network, the role of agents in the structure and function of the network is also different. This metric considers that the more important a agent occupies in the network topology, the greater contribution it makes to the stability of the network, that is, the agent is an important node in the network. Centrality improves the routing performance of a message by forwarding the message using the “status” of agents in the network, which is consistent with the higher the social status of a real social network and the more resources it can make use of.

Figure 3 experimental results show that AOPMSN meets the power law distribution law and satisfies the scale-free network characteristics. However, the number of connections per agent in RW random network is consistent with Poisson’s distribution.

Link lifetime. Link survival time is another metric of complex networks. Figure 4 shows that the AOPMSN model has a stable social relationship between agents

### Table 1. Parameters in the simulator.

| Parameter | Value          |
|-----------|----------------|
| \( N \)   | 30, 50, 100, 150, 200 |
| \( A \) (\( m^2 \)) | 1000 × 1000 |
| \( r \) (m) | 50 m          |
| \( v \) (m/s) | 10 m/tick    |

![Figure 2. Comparison of self-organizing emergence of connected patterns.](image-url)
due to its adoption of an AOPMSN model, so its link survival time is longer than that of the RW model.

Mean of clustering coefficient. Clustering coefficient is a metric to study the stability of complex networks from the perspective of network topology. From the perspective of graph theory, clustering coefficient refers to the probability that any two neighbor agents of an agent in the network are neighbors to each other. It can be seen that the clustering coefficient reflects the tendency of agents to gather together in the network structure. The clustering characteristic of network is that birds of a feather flock together and people flock together.

Figure 5 shows the comparison of clustering coefficients between two networks of AOPMSN and RW. The average clustering coefficient of the AOPMSN model is higher than that of the RW model. However, the random network has almost no clustering characteristics and low density, which indicates that the agents of the whole AOPMSN are independent of each other.

Rescue efficiency. Generally speaking, mobility leads to an increase in the number and time of agents contacting each other, so the coverage area largely depends on the dynamic of agents. With the movement of agents, they can perceive areas in the environment that they could not perceive. As can be seen from Figure 6, AOPMSN has the best coverage since there is some stable social relationship between agents, so sensors spread rapidly in the environment.

Routing performance. In traditional networks, the performance of the routing algorithm is usually evaluated by the length of the network path or the number of hops in the network. However, traditional evaluation criteria cannot be applied based on the specific network characteristics of AOPMSN. In AOPMSN, agents are intermittently connected by chance, and there is a certain delay in the process of transmitting events to the destination agent. Intermittent transmission is also more likely to cause event loss during event transmission. Therefore, under the specific environment background and taking into account the transmission delay, it has become a common standard for algorithm performance evaluation to complete the event forwarding as much as possible.

Event delivery rate (EDR) refers to the proportion of the number of messages that are successfully sent from the source mobile agent to the sink agent in AOPMSN, which accounts for the total number of events that are found and generated in the network.

Event delivery delay (EDD) refers to the time difference between the time when the event message is generated by the source agent and the time when the message
is sent to the destination agent (sink). The delay of message transmission is generally different for different messages and different environmental backgrounds. Therefore, the method of calculating the average delay is generally used as the evaluation standard of message transmission delay.

EDR. The EDR is defined as the proportion of events that can be reported by the autonomous agents within the time limit. We deployed \( n \) event in the environment. When all events are received by sink, the simulation stops. The results in Figure 7 show that when the number of autonomous agents is only 30, due to the low connectivity of the network, the EDR is very low. With the increase in the number of agents, the network tends to be connected, and the EDR is close to 100%.

Event delivery time. The results show that when the number of autonomous agents is only 30, due to the low connectivity of the network, the event submission time is very long. With the increase in the number of autonomous agents, the network tends to be connected, and the event will be submitted soon. When \( n = 200 \), the event submission time is 36 ticks. The convergence process of the submitted algorithm is shown in Figure 8. The test also verifies the effectiveness of the algorithm.

Conclusion
This article proposes an AOPMSN in smart city for emergency rescue. The autonomy and mobility of AOPMSN lead to its complexity. By studying the single autonomous user modeling problem of AOC model, the self-organizing interaction of multiple autonomous agents in AOC model is studied. This article studies how the four network mechanisms of homogeneity, resource dependence, community priority attachment, and new location exploration affect each other to emerge the global network structure.

This article verifies that the AOPMSN model has the performance of social network from four different metrics: connectivity mode, agent degree distribution, link lifetime, and clustering coefficient. The model depicts the characteristics of human mobility, such as self-organization, scale-free, aggregation, and community structure. The rescue efficiency is discussed through the coverage area of the mobile sensor. Finally, the performance of the routing protocol based on AOPMSN model is analyzed by two metrics: EDR and event transmission delay, which proves the effectiveness of the method.

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