A Four-quadrant Mobility Model-based Routing Protocol for Post-earthquake Emergency Communication Network

Xiaoming Wang
Shanghai Earthquake Administration https://orcid.org/0000-0002-8328-3805
Chang Guo (guochang@mail.dhu.edu.cn)
Ping Li
Shanghai Earthquake Agency

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A four-quadrant mobility model-based routing protocol for post-earthquake emergency communication network

Xiaoming Wang [1], Chang Guo[2,*], Ping Li[1]

[1] Shanghai Earthquake Administration; wangyoucao78@163.com
[2] The College of Information, Mechanical, and Electrical Engineering, Shanghai Normal University; guochang@mail.dhu.edu.cn
* Correspondence: guochang@mail.dhu.edu.cn

Abstract: Emergency communication network (ECN) is essential for both disaster victims and rescuers since the pre-deployed network infrastructure may be completely destroyed after the earthquake. Traditional protocols cannot satisfy the requirements of ECN as they neither consider mobility model nor seismic intensity. In this paper, a four-quadrant mobility model (FQMM) based on seismic intensity is proposed for rescuers. Then a FQMM-based protocol (FQMMBP) for ECN is designed, which aims to improve the performance of ECN. Simulation results show that the proposed protocol performs better than other three compared routing protocols (AODV, DSDV and DSR) in package delivery rate (PDR) and end-to-end delay. Although the performance of FQMMBP in overhead is not as good as the other three protocols, it is worthwhile for the emergency rescue.

Keywords: ECN; FQMM; FQMMBP; Rescue Urgency Degree; post-earthquake

1. Introduction

After the devastating earthquake, emergency rescue crews are needed to rush to the scene for rescue as soon as possible. Post-earthquake emergency rescue includes material dispatching, team dispatching, personnel evacuation, post-disaster reconstruction, etc. Due to the different catastrophic degrees caused by the earthquake in different affected areas, the Rescue Urgency Degrees (*RUDs*) are different for those areas. Seismic intensity, which refers to the catastrophic degree of earthquake impact on the ground or artificial buildings in a certain area [1], can be used to express the rescue urgencies of disaster areas. The seismic intensity can be obtained in the following ways [2]: In the area where seismic observation equipment is intensively deployed, we can directly obtain the intensity distribution map of the instrument; In the area where seismic observation equipment is sparsely deployed, we can obtain the intensity distribution map of the instrument by grid interpolation; In the area where seismic observation equipment is rarely deployed, we can obtain the intensity distribution map either by historical seismic data statistics or earthquake simulations. Therefore, it is feasible to carry out emergency rescue according to the emergency degree of the disaster area reflected by seismic intensity.

After the devastating earthquake, the communication infrastructure and power system in the disaster area will suffer from different degrees of damage, resulting in communication system paralysis. Rescue crews have to quickly establish ECN in the disaster area to meet the communication demands both inside and outside the affected area.

Unlike traditional self-organized network, the nodes in ECN have the characteristics of energy limitation, high energy consumption in communication and low energy consumption in data calculation. In recent years, the research on ECN routing protocols has been widely concerned by scholars.

2. Related works

In the existing research on the mobility model of emergency rescue crews, the traditional task assignment model, e.g., numerical type [3], time window [4] and linear time satisfaction function [5], usually focuses on processing of rescue time. Song Ye et al. [6] established an optimization model for the assignment of earthquake emergency rescue teams, aiming at improving rescue efficiency and maximizing the satisfaction of rescue time. Pan Xinchao et al. [7] established an optimal scheduling model for earthquake emergency rescue based on the precondition of rescue capability constraints, expecting to treat as more wounded as possible in the shortest time. Li Mingyang et al. [8] comprehensively considered the satisfaction of emergency rescue time and the competence of rescue crews, and then established the dispatch and distribution model of emergency rescue crews, which solved the dispatch problem of emergency rescue crews with multiple disaster areas. Li Jin et al. [9] established a multi-resource and multi-disaster-point emergency scheduling model for resource scheduling in emergency scenarios, and designed a heuristic algorithm based on network optimization and linear programming optimization ideas in graph theory to reasonably schedule disaster relief resources and minimize the loss of life and property. Cao Qingkui et al. [10] proposed the experience satisfaction model of disaster victims to schedule the rescue crews, aiming at obtaining the maximum experience satisfaction and the best rescue result. However, the above researches studied the mobility models from the perspective of rescue capacity and relief materials repertory, without considering seismic intensity in disaster areas. Furthermore, the above researches did not reasonably allocate the communication and rescue nodes based on the characteristics of ECN.

In the field of ECN protocol investigation, Li Mufeng et al. [11] studied the energy consumption of nodes in emergency communication scenarios. Based on the DCHS (deterministic cluster head selection) protocol, the link quality was introduced into the communication cost function, and a shortest path non-uniform clustering algorithm based on link quality was proposed to extend the lifetime of ECN by saving energy. Xue Lisi et al. [12] took Ya'an earthquake as an example, established different earthquake emergency communication models in earthquake by analyzing the topography of Sichuan Province, and screened out the multi-copy routing protocol which was suitable for earthquake emergency communication in Sichuan Province. Yu Xiang et al. [13] improved AODV protocol for emergency communication scenarios, and proposed SE-AODV protocol which can reduce energy consumption and extend lifetime in ECN. Xiaoming Wang et al. [14] proposed a two-stage extended forwarding dynamic routing protocol based on the degree of social activity and physical contact factors of mobile users, which not only significantly improved the delivery rate of messages, but also reduced the cost ratio and average delay of messages. In ECN, the routing discovery process of on-demand routing protocol is expensive, and the energy consumption of nodes is large. In order to solve the above problems, R. Ramalakshmi et al. [15] proposed a weighted low-power routing protocol. The protocol selected the maximum weighted and minimum connected control set of network nodes based on the weights, which consisted of link stability, mobility and energy. Simulation results showed that the protocol was superior to other protocols in packet delivery rate, control message overhead, transmission delay and energy consumption. Dhafer Ben Arbia et al. [16] proposed a new multi-hop routing protocol for ECN, through which an ad-hoc network between rescue crews and command center was established. The routing table was optimized based on real-time end-to-end link quality estimation. Compared with other routing protocols, the proposed protocol was superior in packet received rate and energy consumption, which extended lifetime and enhanced reliability of ECN. Vipin bondre et al. [17], B. Ramakrishnan et al. [18] analyzed the performance of AODV, DSR, DSDV and other traditional routing protocols in emergency scenarios. However, they did not consider the mobility model of rescuers, nor the *RUDs* (Rescue Urgency Degrees) in disaster areas.

In this paper, we first propose a seismic intensity based four-quadrant rescue mobility model (FQMM), then we simulate earthquake scene and propose a FQMM-based protocol for ECN. The main contributions of this paper are as follows:

Firstly, this paper gives the topology of ECN for the scene of post-earthquake emergency rescue.

Secondly, the FQMM mobility model for post-earthquake emergency rescue crews is proposed, which based on the topological structure of ECN.

Finally, this paper proposes a FQMM-based protocol (FQMMBP) for ECN. According to the location of the mobile node, FQMMBP predicts hop counts from source to destination, so that it can update the routing table in real time by selecting the optimal next-hop node, thus improving package delivery rate, reducing end-to-end delay.

Although the routing protocol proposed in this paper only considers the factor of seismic intensity, the designed mobility model is universal and can be applied to other natural disasters, such as floods, fires, typhoons and so on.

3. Method

3.1. Scenario and Assumptions

In the post-earthquake ECN, the emergency communication vehicle (ECV) and base station (BS) are regarded as fixed nodes, while rescue crews equipped with individual communication equipment are regarded as mobile nodes. Unmanned Aerial Vehicle (UAV) can be used not only as a fixed node for relaying communication, but also as a mobile node for collecting disaster information. A typical post-earthquake ECN is shown in Figure 1.

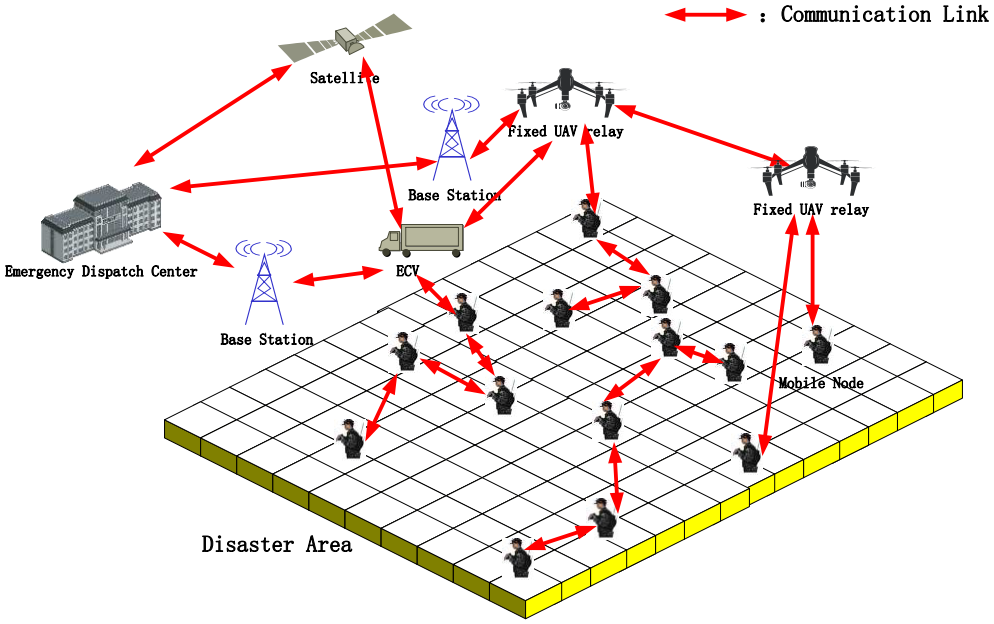

Figure 1. An example of post-earthquake ECN

After the earthquake, rescuers equipped with individual communication equipment were scattered to various disaster areas for rescue. Each communication node in ECN, such as ECV, UAV and portable individual equipment (PIE), has its own communication coverage. Since ECV cannot reach the center of the disaster area due to traffic control, it starts at the midpoint of length, where rescue crews start and stop rescue missions, as shown in Figure 2. In the rescue process, ECV can provide real-time communication for rescue crews. Due to its mobility and air superiority, UAV can go deep into the disaster area and play the role of communication relay or disaster information collector. However, due to the limited battery capacity and high costs of UAV, we are unable to deploy a large number of UAVs in the disaster area. Rescuers can enter the disaster area with PIE, however, due to the limited coverage, high cost and large energy consumption, PIE cannot play the role of hot spot or relay for a long time. Therefore, how to cooperate with the communication equipment in ECN to improve the communication efficiency is one of the key issues that need to be paid attention to in post-earthquake emergency rescue. Therefore, heterogeneous communication devices in ECN need to cooperate with each other through appropriate routing protocols to improve communication efficiency. The symbols used in this paper are listed in Table 1.

Table 1. Parameter definition and description

Parameters	Description
RUD	Rescue Urgency Degree, which is inversely proportional to the seismic intensity value in this area. The closer the area is to the epicenter, the lower the value of *RUD* is, which means the disaster is serious and the priority of rescue is high; Otherwise, the opposite. When *RUD* = 1, the epicenter disaster area is a rectangle; When *RUD* > 1, the disaster areas are rectangle rings that expands outwards in turn.
a_i	Length of area where *RUD*=*i*.
b_i	Width of area where *RUD*=*i*.
QL	Quadrant Level, which is the number of times the quadrant divided.
QID	Quadrant ID.
RT	Number of Rescue Tasks.
NRA	Number of Rescuers Allocated.
M	Number of mobile nodes.

After the earthquake, we use rectangle to represent the earthquake influence range. The length and width of the rectangle are a_i and b_i (i=1…n) respectively. Before studying the mobile model, we propose the following assumptions for simulation calculation:

Assumption 1: In the region with equal seismic intensity, the value of *RUD* is equal.

Assumption 2: Each rescuer has got equal rescue efficiency.

Assumption 3: Rescue tasks in low *RUD* areas are at high priority. Rescue crews cannot start rescue tasks in higher *RUD* areas until rescue tasks in low *RUD* areas are completed.

Assumption 4: Random waypoint mobility model [19] for rescuers is used in each disaster area. In order to ensure the fairness and rationality of the rescue sequence, the rescuers are approximately evenly distributed in disaster areas with equal *RUD* values.

Assumption 5: Locations and number of rescue tasks are known by rescue crews in advance, since the Global Positioning System (GPS) is used.

Based on seismic intensity and number of rescuers in disaster areas, this paper proposes a four-quadrant mobility model of rescue crews, which improves the rescue efficiency and ensures the safety of the victims' lives and properties. The proposed mobility model mainly includes two aspects: Firstly, the most seriously affected areas are rescued as soon as possible; secondly, the rescue crews are allocated to each appropriate quadrant, which improves the rescue efficiency and shortens the time of rescue.

3.2. Disaster area division

Disaster area is divided into n layers according to seismic intensity. The epicenter is located in the first layer (*RUD*=1) where length is a_1 and width is b_1. We define *RUD* of each region as 1, 2,…, n. Epicenter located at the center of rectangle where *RUD*=1. All areas are rectangular rings, except for the one with *RUD*=1, which is a rectangle. ECV parks at the midpoint of the length outside the rectangular ring with *RUD*=n, as shown in Figure 2.

The length and width of each disaster area are marked as $\{RUD|\ a_i, b_i\}$, then each region can be expressed as follows:

Region 1：$\{RUD=1|\ a_1, b_1\}$;

Region 2：$\{RUD=2|\ a_2 = a_1 + \frac{a_1}{2} + \frac{a_1}{2} = 2a_1, b_2 = b_1 + \frac{b_1}{2} + \frac{b_1}{2} = 2b_1\}$;

Region 3：$\{RUD=3|a_3 = a_2 + \frac{a_2}{2} + \frac{a_2}{2} = 2a_2 = 4a_1, b_3 = b_2 + \frac{b_2}{2} + \frac{b_2}{2} = 2b_2 = 4b_1\}$;

According to mathematical induction, we can get:

Region i：$\{RUD=3|a_i = 2a_{i-1} = 2^{i-1}a_1,\ b_i = 2b_{i-1} = 2^{i-1}b_1\}$.

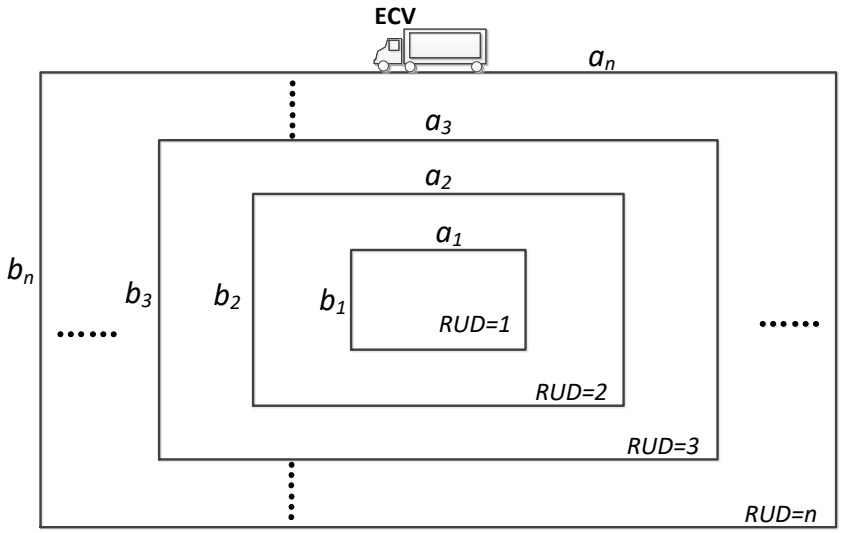

Figure 2. Disaster area division according to *RUD*

3.3. Four-quadrant mobility model (FQMM)

In this section, a four-quadrant rescuers allocation scheme is proposed. Based on this scheme, a four-quadrant mobility model (FQMM) for rescuers is proposed. The objectives of the allocation scheme are: 1) carrying out grid search in disaster areas to ensure the effectiveness of rescue without missing any victims; 2) carrying out radiation diffusion rescue from epicenter to ensure the worst affected areas are on top of the rescue list. From the disaster area division discussed in Section 3.2, it can be seen that when *RUD*=1, the region is a rectangle, and when *RUD*>1, the regions are rectangular rings. Therefore, the discussion of rescuers allocation scheme include two aspects: *RUD*=1 and *RUD*>1. The core ideas of rescuers allocation scheme for regions with *RUD*>1 are similar, though the lengths of the regions are different.

3.3.1. Mobility model for rescuers in regions with *RUD*=1

Five steps (**Step 1** to **Step 5**) are included in the mobility model of rescuers for regions with *RUD*=1.

Step 1: As shown in Figure 3, we establish a coordinate system which takes the epicenter as the origin. *X* and *Y* axes are the length and width of the rectangle. Four quadrants, *QID* = 1, *QID* = 2, *QID* = 3 and *QID* = 4 are counter-clockwise defined according to the definition of coordinate system. Each quadrant is described as follows:

Quadrant 1：{*RUD*=1| *QID* =1}；Quadrant 2：{*RUD*=1| *QID* =2}；Quadrant 3：{*RUD*=1| *QID* =3}；Quadrant 4：{*RUD*=1| *QID* =4}。

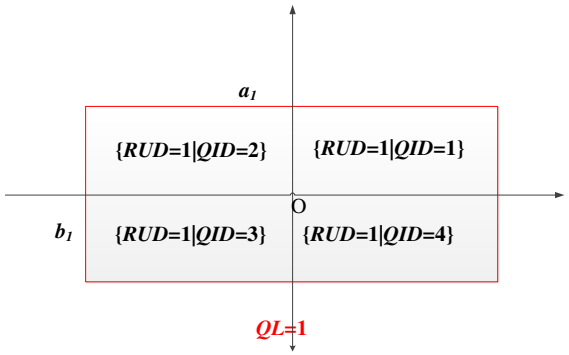

Figure 3. Disaster area with *RUD*=1 is divided into 4 quadrants for the first time (*QL*=1)

Suppose that the total number of rescuers is M, and the total number of rescue tasks in the area with RUD = 1 is Q, which is, $RT_{QL=0}^{RUD=1} = Q$, where $RT_{QL=0}^{RUD=1}$ stands for total number of rescue tasks to be completed in disaster areas with RUD=1 and QL=0. The number of tasks to be performed in each quadrant is described as: $RT_{QID=k}^{RUD=1} = \lceil Q/4 \rceil$, $(k = 1, 2, 3, 4)$, where $RT_{QID=k}^{RUD=1}$ stands for the number of tasks to be performed in disaster areas with RUD=1 and QID=k (k=1, 2, 3, 4). Rescuers are evenly allocated to four quadrants with QL=1, and the number of rescuers allocated (NRA) in each quadrant can be discussed from four cases (**Case 1** to **Case 4**) as follows:

Case 1: Mod[M/4]=0, where function Mod[x/y] is used to return the remainder of the division of two numbers x, y. In this case, a quarter of rescuers are evenly allocated to four quadrants with QL=1, which is:

$$NRA_{QID=k}^{RUD=1} = \frac{M}{4}, \quad (k = 1, 2, 3, 4)$$

where $NRA_{QID=k}^{RUD=1}$ stands for the number of rescuers allocated in each quadrant with RUD=1 and QID=k.

Case 2: Mod[M/4]=1. In this case, one more rescuer is allocated to Quadrant 1, which are:

$$NRA_{QID=1}^{RUD=1} = \frac{M-1}{4} + 1$$

$$NRA_{QID\neq 1}^{RUD=1} = \frac{M-1}{4}$$

where $NRA_{QID=1}^{RUD=1}$ stands for the number of rescuers allocated in Quadrant 1 with RUD=1, and $NRA_{QID\neq 1}^{RUD=1}$ stands for the number of rescuers allocated in Quadrant 2, Quadrant 3 and Quadrant 4 with RUD=1.

Case 3: Mod[M/4]=2. In this case, one more rescuer is allocated to Quadrant 1 and Quadrant 2 respectively, which are:

$$NRA_{QID=1\ or\ 2}^{RUD=1} = \frac{M-2}{4} + 1$$

$$NRA_{QID=3\ or\ 4}^{RUD=1} = \frac{M-2}{4}$$

where $NRA_{QID=1\ or\ 2}^{RUD=1}$ stands for the number of rescuers allocated in Quadrant 1 and Quadrant 2 with RUD=1, and $NRA_{QID=3\ or\ 4}^{RUD=1}$ stands for the number of rescuers allocated in Quadrant 3 and Quadrant 4 with RUD=1.

Case 4: Mod[M/4]=3. In this case, one more rescuer is allocated to Quadrant 1, Quadrant 2, Quadrant 4, which are:

$$NRA_{QID\neq 3}^{RUD=1} = \frac{M-3}{4} + 1$$

$$NRA_{QID=3}^{RUD=1} = \frac{M-3}{4}$$

where $NDN_{QID\neq 3}^{RUD=1}$ stands for the number of rescuers allocated in Quadrant 1, Quadrant 2 and Quadrant 4 with RUD=1, and $NRA_{QID=3}^{RUD=1}$ stands for the number of rescuers allocated in Quadrant 3 with RUD=1.

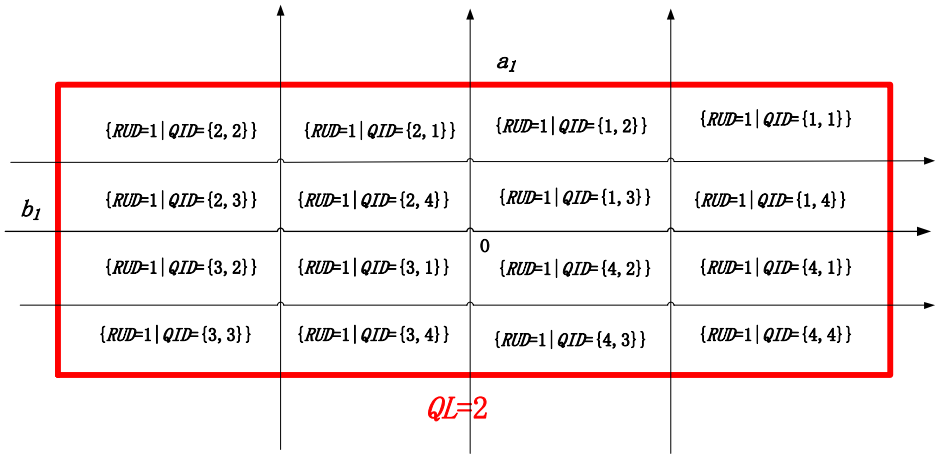

Figure 4. Disaster area with RUD=1 is divided into 16 quadrants for the second time (QL=2)

Step 2: According to the procedure of step 1, each quadrant with *RUD*=1 is further divided into four secondary quadrants as shown in Figure 4. Two elements are included in *QID* set, which record the quadrant ID from the first level to the last level. For example, {*RUD*=1|*QID*={1,3}} in Figure 4 means region with *QL*=1 is located in Quadrant 1 and region with *QL*=2 is located in Quadrant 3.

Step 3: For *QL*=*x*, replace the value of *M* with $RT_{QL=x}^{RUD=1}$, repeat Step 1 and calculate the number of rescuers allocated for each quadrant with *QL*=*x*.

Step 4: Repeat **Step 2** and **Step 3**, until any of the following **Abort Conditions** is satisfied.

Abort Condition 1: There is only one rescuer in each area of quadrant with *QL*=*x*, which is: $NRA_{QID=k}^{RUD=1}=1$，（$k=1$，2，3，4），where $NRA_{QID=k}^{RUD=1}$ is the number of rescuers allocated in Quadrant *k* (*k*=1, 2, 3, 4) with *RUD*=1 and *QL*=*x*. Under this condition, further quadrant division is no longer meaningful, so the single rescuer will complete all rescue tasks in the region of quadrant with *QL*=*x*.

Abort Condition 2: The number of rescue tasks is less than that of rescuers assigned in the quadrant with *QL*=*x*, which is: $NRA_{QID=k}^{RUD=1}\geq RT_{QID=k}^{RUD=1}$，（$k=1$，$2$，$3$，$4$），where $NRA_{QID=k}^{RUD=1}$ is the number of rescuers allocated in Quadrant *k* (*k*=1, 2, 3, 4) with *RUD*=1 and *QL*=*x*, and $RT_{QID=k}^{RUD=1}$ is number of rescue tasks in Quadrant *k* (*k*=1, 2, 3, 4) with *RUD*=1 and *QL*=*x*. Under this condition, each rescuer is assigned to at most one rescue task, and there are unoccupied rescuers in the area.

Step 5: Quadrant division is suspended and rescuers begin to perform their own rescue tasks.

Figure 5 shows the algorithm flow of rescue node allocation in rectangular disaster area when *RUD* = 1.

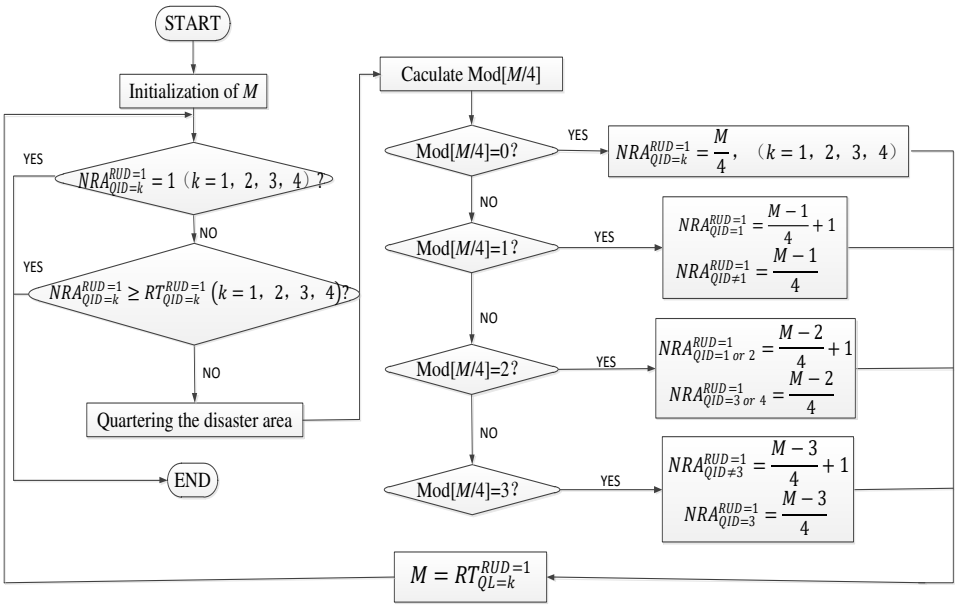

Figure 5. Allocation process of rescue nodes in disaster area with *RUD*=1

3.3.2. Mobility model for rescuers in regions with *RUD*>1

According to the mobility model, rescue crews cannot start rescue tasks in higher *RUD* areas until rescue tasks in low *RUD* areas are completed. As shown in Figure 6, in the gray area with *RUD*=1, rescuers are carrying out rescue tasks. When the task is over, rescuers will be assigned to the white rectangular ring area with *RUD*=2.

Five steps (**Step 6** to **Step 10**) are included in the mobility model of rescuers for regions with *RUD*>1.

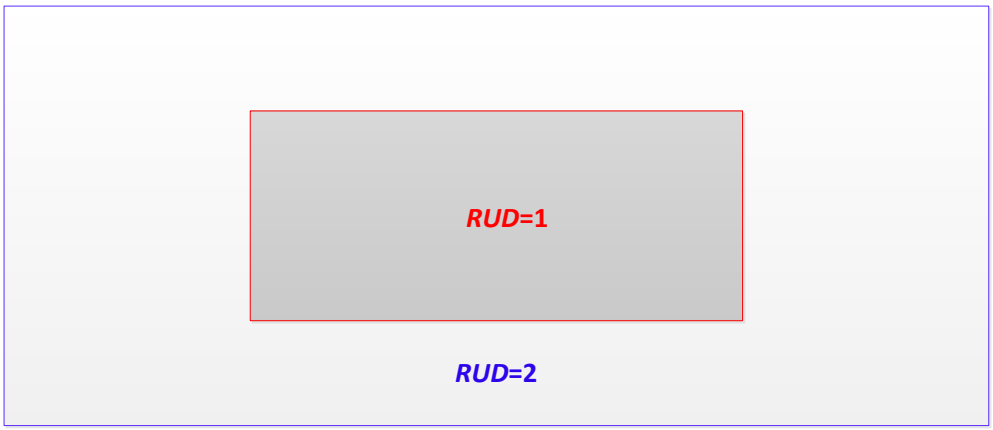

Figure 6. Rectangular ring with *RUD*>1

Step 6: As shown in Figure 7, we establish four coordinate systems which takes O_1, O_2, O_3 and O_4 as the origins respectively. Then the rectangular ring is equally divided into twelve quadrants (the white parts in Figure 7) by four coordinate systems. In each coordinate system, four quadrants are equal with each other in area, as shown in Figure 7 where four triangle marks.

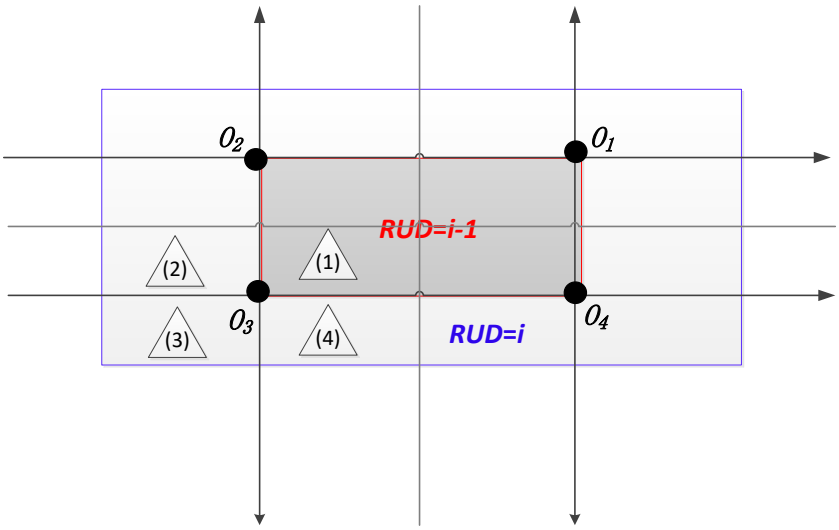

Figure 7. Disaster area with *RUD*>1 is divided into 12 quadrants for the first time (*QL*=1)

Step 7: It can be seen from **Step 6** that in each coordinate system, there are three quadrants waiting for allocation of rescuers, and the left quadrant is allocated with rescue crews. As shown in Figure 7, in the coordinate system with O_3 as origin, there are four quadrants where Triangle (1), Triangle (2), Triangle (3) and Triangle (4) marks. Area where Triangle (1) marks is allocated with rescue crews, while areas where Triangle (2), Triangle (3) and Triangle (4) marks are waiting for rescuers allocations. We take coordinate system O_3 as an example. Suppose there are M rescuers in Quadrant 1 with *RUD*=*i*-1, which marked with Triangle (1). There are Q rescue tasks in areas with *RUD*=*i*, which is: $RT_{QL=0}^{RUD=i} = Q$. Rescuers are evenly allocated to three quadrants (Triangle (2), Triangle (3) and Triangle (4)) with *QL*=1, and the number of rescuers allocated (*NRA*) in each quadrant can be discussed from three cases (**Case 5** to **Case 7**) as follows:

Case 5: Mod[M/3]=0, where function Mod[x/y] is used to return the remainder of the division of two numbers x, y. In this case, one-third rescuers are evenly allocated to three quadrants, which is:

$$NRA_{QID=k}^{RUD=i} = \frac{M}{3}, \quad (k = 2,\ 3,\ 4)$$

where $NRA_{QID=k}^{RUD=i}$ stands for the number of rescuers allocated in each quadrant with *RUD*=*i* and *QID*=*k*.

Case 6: Mod[*M*/3]=1. In this case, one more rescuer is allocated to Quadrant 2, which are:

$$NRA_{QID=2}^{RUD=i} = \frac{M-1}{3} + 1$$

$$NRA_{QID=3\ or\ 4}^{RUD=i} = \frac{M-1}{3}$$

where $NRA_{QID=2}^{RUD=i}$ stands for the number of rescuers allocated in Quadrant 2 with *RUD*=*i*, and $NRA_{QID=3\ or\ 4}^{RUD=i}$ stands for the number of rescuers allocated in Quadrant 3 and Quadrant 4 with *RUD*=*i*.

Case 7: Mod[*M*/3]=2. In this case, one more rescuer is allocated to Quadrant 2 and Quadrant 4 respectively, which are:

$$NRA_{QID=2\ or\ 4}^{RUD=i} = \frac{M-2}{3} + 1$$

$$NRA_{QID=3}^{RUD=i} = \frac{M-2}{3}$$

where $NRA_{QID=2\ or\ 4}^{RUD=i}$ stands for the number of rescuers allocated in Quadrant 2 and Quadrant 4 with *RUD*=*i*, and $NRA_{QID=3}^{RUD=i}$ stands for the number of rescuers allocated in Quadrant 3 with *RUD*=*i*. The number of rescue tasks in each quadrant with *RUD*=*i* is: $RT_{QID=k}^{RUD=i} = \lceil Q/12 \rceil$，（$k = 2，3，4$），where $RT_{QID=k}^{RUD=i}$ stands for the number of rescue tasks in Quadrant *k* (*k*=2, 3, 4) with *RUD*=*i*.

Step 8: Quadrants (*QL*⩾2) division methods are the same as illustrated in **Step 6**, which take the middle points of quadrants with *QL*=1 as the origins and establish the coordinate systems. Repeat **Step 7**, until any of the following **Abort Conditions** is satisfied.

Abort Condition 3: There is only one rescuer in each area of quadrant with *QL*=*x*, which is: $NRA_{QID=k}^{RUD=i} = 1$，（$k = 1，2，3，4$），where $NRA_{QID=k}^{RUD=i}$ is the number of rescuers allocated in Quadrant *k* (*k*=1, 2, 3, 4) with *RUD*=*i* and *QL*=*x*. Under this condition, further quadrant division is no longer meaningful, so the single rescuer will complete all rescue tasks in the region of quadrant with *QL*=*x*.

Abort Condition 4: The number of rescue tasks is less than that of rescuers assigned in the quadrant with *QL*=*x*, which is: $NRA_{QID=k}^{RUD=i} \geq RT_{QID=k}^{RUD=i}$，（$k = 1，2，3，4$），where $NRA_{QID=k}^{RUD=i}$ is the number of rescuers allocated in Quadrant *k* (*k*=1, 2, 3, 4) with *RUD*=*i* and *QL*=*x*, and $RT_{QID=k}^{RUD=i}$ is number of rescue tasks in Quadrant *k* (*k*=1, 2, 3, 4) with *RUD*=*i* and *QL*=*x*. Under this condition, each rescuer is assigned to at most one rescue task, and there are unoccupied rescuers in the area.

Step 9: Quadrant division is suspended and rescuers begin to perform their own rescue tasks.

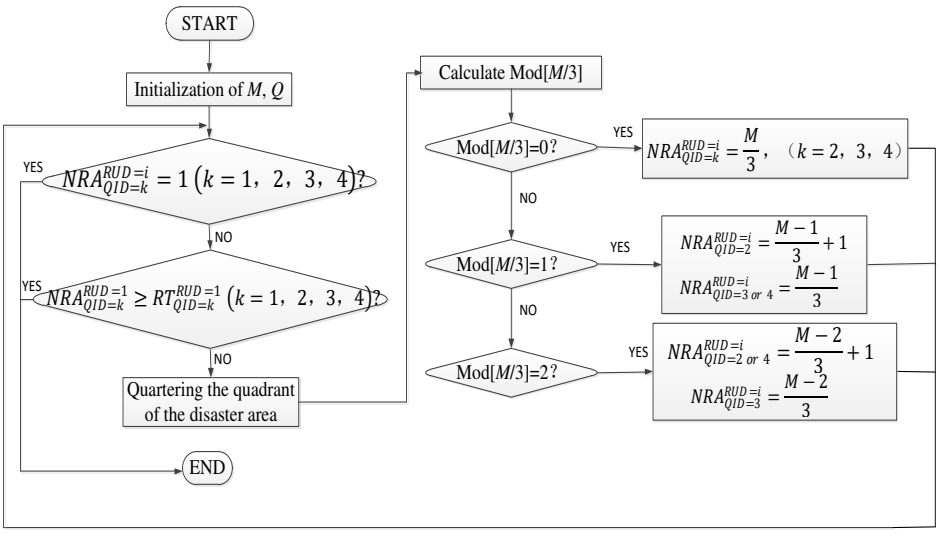

Figure 8. Allocation process of rescue nodes in disaster area with *RUD*>1

Figure 8 shows the algorithm flow of rescue node allocation in rectangular disaster area when *RUD*>1.

4. FQMM-based routing protocol

4.1. backgrounds

Post-earthquake ECN, which is a hybrid self-organized network, mainly includes ECV, UAV, portable devices carried by rescue crews, base station, satellite, etc. Those communication devices and be classified as fixed communication nodes (such as ECV, base station, UAV used for relay, etc.) and mobile communication nodes (such as portable devices carried by rescue crews, satellite, etc.). As shown in Figure 1, each portable device is equipped with a wireless communication module. Rescuers can use portable devices to build self-organized networks, through which they can communicate with each other and complete the transmission process of data packets, such as receiving, transmitting and relaying. Rescuers can also communicate with ECV, UAV and other fixed nodes within the coverages of portable devices. As a fixed communication node, ECV can communicate with rescuers and UAVs in the disaster area through downlink, or with the base station, satellite and other communication facilities through uplink. Through the backbone network, commanders can get the information about rescue crews, rescue process and suffering condition in time, so as to make scientific rescue decision and emergency response quickly.

We define the communication radius of mobile node as *R*. The mobile node sends data to the emergency communication vehicle in the way of multi-hop. In such communication mode, the source is the mobile node in the disaster area, the destination is ECV at the edge of the disaster area, and the relay nodes are mobile nodes or fixed nodes (UAVs, etc.) in the disaster area. On the premise of ensuring the stability of communication links, we choose relay nodes or links that can minimize the delay for data transmission. Based on the mobility model we discussed in Section 3.3, it can be seen that rescue crews are nearly evenly distributed in disaster areas with the same *RUD*. In order to ensure the stability of the communication link in the rescue process, we place fixed UAVs at the edges of disaster areas with different *RUD* values; however, they do not undertake the rescue tasks. When all rescue tasks in the disaster area with a specific *RUD* value are completed, the relay UAV in the area returns to the location of ECV.

4.2. Protocol design

In this section, a proposal of FQMM-based protocol (FQMMBP) for ECN is presented. First, we discuss route discovery and maintenance of FQMMBP, and then we propose FQMMBP protocol by analyzing the communication mechanism of nodes in ECN.

4.2.1. Route discovery and maintenance

In order to reduce the data transmission delay, we select the next hop relay node according to *RUD* value, *QL* and *QID* of each region where mobile nodes are located in. *RUD* and *QL* are used to define the level of the region where mobile nodes are located in. *QID* is a set which includes 1, 2, 3 and 4, and there are *QL* elements in the set. According to the set, the mobile nodes learn the division of the regions and the quadrants position, so as to select the appropriate next hop mobile node. Therefore, in the process of routing discovery, it is necessary to extend the routing request (RREQ) message, so as to meet the requirements of our proposed communication mechanism of FQMMBP. We improved the traditional RREQ message by adding four new fields: *RUD*, *QL*, *QID* and *QW*. *RUD* describes the area where nodes are located and judge whether the area is a rectangle or a rectangular ring as shown in Figure 2. *QL* describes the level of the quadrant where nodes are located, and it determines the relative position of the mobile rescue node. *QID* describes the division of the quadrant where nodes are located and judge its relative position to ECV. When the *QL* of quadrants are the same, *QID* helps pick up the mobile rescue node which is closer to ECV. *QW* calculates weights of nodes according to *QL* and *QID*, so as to select the most appropriate next-hop relay node.

In the process of route discovery, nodes broadcast RREQ messages to send request information to their neighbors. The improved RREQ data format is shown in Table 2.

Each field of RREQ data format is described as follows:

Type: The length of this field is 8bit, and the type value of RREQ is 1

Flags: The length of this field is 5 bits, and five identities (J, R, G, D, and U) are included in this field. "J" is a joint flag and is generally used for multicast. "R" is for route repairing and is used for multicast transmission. "G" represents the list of nodes around ECV which can be communicated. Flag "G" determines whether the RREQ message can be directly sent to the destination or not. "D" is the reply flag of the destination node which determines whether the destination node is allowed to reply to the received RREQ message or not. "U" is the flag of unknown serial number. U=1 means that the serial number of the node is unknown.

Reserved: Reserved field for further improvement of RREQ message.

Hop Count: This field registers the hop counts that RREQ passes from the source node to the current node.

RREQ ID: This field is the unique identity of RREQ message.

RUD: Rescue Urgency Degree, which is inversely proportional to the seismic intensity value in this area.

QL: Quadrant Level, which is the number of times the quadrant divided.

QID: Quadrant ID.

QW: Weights of nodes in quadrant.

Table 2. The improved RREQ data format.

Type	Flags					Reserved	Hop Count
	J	R	G	D	U		
RREQ ID							
Destination IP Address							
Destination Sequence Number							
Source IP Address							
Source Sequence Number							
RUD							
QL							
QID							
QW							

4.2.2. Communication mechanism of mobile node

As shown in Table 2, for fixed UAV nodes located in different *RUD* areas, all fields of RREQ message are empty except for "*RUD*". The "*RUD*" field describes the UAV's location. Suppose that there is one UAV relay node in each region with *RUD*=*i* (*i*=1 to *n*), and the UAVs in two adjacent regions can communicate with each other directly. Then there are *n* + 1 fixed communication nodes in the disaster area (*n* fixed UAVs and one ECV). Mobile nodes in regions with *RUD*=*i* (*i*=1 to *n*) can transmit data to the fixed UAV node either by one hop or by multiple hops. After that, the data can be transmitted to ECV through multi-hop between fixed nodes without relying on other mobile nodes. In that case, we need to select the most appropriate next hop relay node (mobile node or fixed node) when the next hop candidate is in different quadrants. It can be seen from Figure 2 that Quadrant 1 and Quadrant 2 are closer to ECV than Quadrant 3 and Quadrant 4, so the weights of Quadrant 1 and Quadrant 2 should be greater than that of Quadrant 3 and Quadrant 4. As shown in Figure 9, the distance between the center of each quadrant and ECV is:

$$D_{QID} = \begin{cases} c & QID = 1 or 2 \\ d & QID = 3 or 4 \end{cases} \quad (1)$$

$$c = \sqrt{\left(\frac{a}{4}\right)^2 + \left(\frac{b}{4}\right)^2} \quad (2)$$

$$d = \sqrt{\left(\frac{a}{4}\right)^2 + \left(\frac{3b}{4}\right)^2} \quad (3)$$

where a, b are length and width of disaster area respectively. D_{PH} stands for the distance between the center of each quadrant and ECV. c is the distance between the center of Quadrant 1 and ECV, which equals with the distance between the center of Quadrant 2 and ECV. d is the distance between the center of Quadrant 3 and ECV, which equals with the distance between the center of Quadrant 4 and ECV. Take the weight of Quadrant 1 (or Quadrant 2) as the benchmark, which is: $W_{QID=1\ or\ 2} = 1$, where $W_{QID=1\ or\ 2}$ is the weight of Quadrant 1 or Quadrant 2. The weight of Quadrant 3 (or Quadrant 4) can be expressed as:

$$W_{QID=3\ or\ 4} = \frac{d}{c} = \frac{\sqrt{a^2+9b^2}}{\sqrt{a^2+b^2}} \quad (4)$$

where $W_{QID=3\ or\ 4}$ is the weight of Quadrant 3 or Quadrant 4.

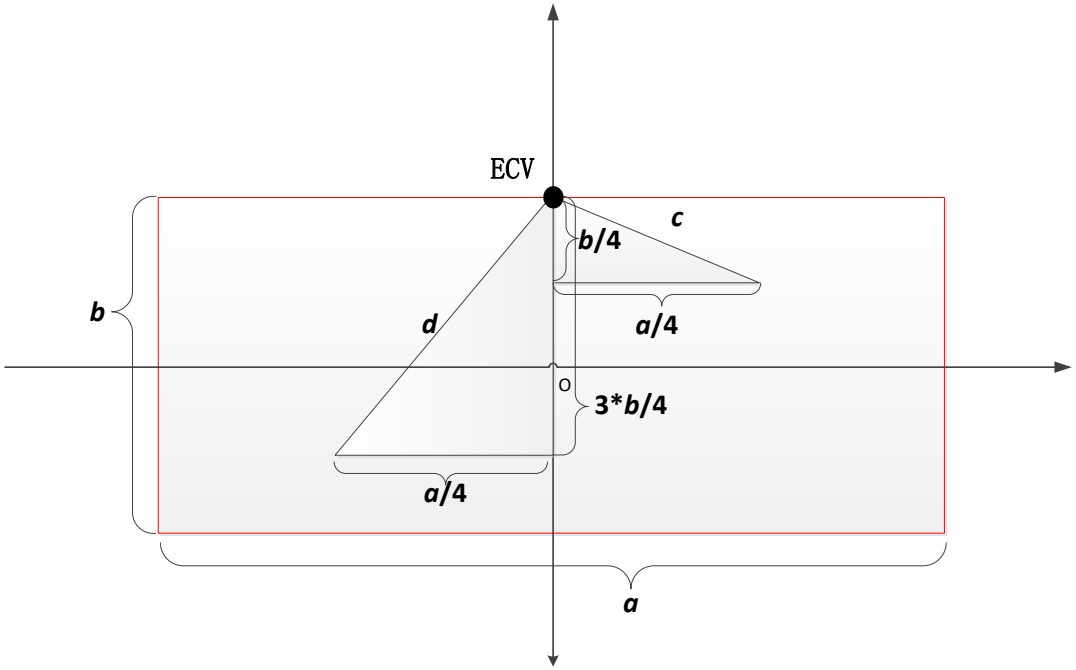

Figure 9. Calculate the weight of each quadrant according to the distance from quadrant center to ECV

Definition: QID_i is the Quadrant ID with QL=i. For example, $QID_3 = 4$ means Quadrant 4 is with QL=3. From Eq.(1) and Eq.(4), we can get:

$$D_{QID_i} = \begin{cases} c_i & QID_i = 1or2 \\ d_i & QID_i = 3or4 \end{cases} \quad (5)$$

where D_{QID_i} stands for the distance between the center of quadrant with QID_i and ECV. c_i is distance between the center of Quadrant 1 with QL=i and ECV, which equals with the distance between the center of Quadrant 2 with QL=i and ECV. d_i is distance between the center of Quadrant 3 with QL=i and ECV, which equals with the distance between the center of Quadrant 4 with QL=i and ECV. From Eq.(4), we can get:

$$W_{QID_i} = \frac{\sqrt{{a_i}^2+9{b_i}^2}}{\sqrt{{a_i}^2+{b_i}^2}} \quad (6)$$

where W_{QID_i} is the weight of node located in Quadrant QID_i. a_i, b_i are length and width of disaster area with QL=i respectively. According to the QID and QL, we can get the total weight of each node in quadrants with different levels by:

$$QW = \sum_{i=1}^{QL} W_{QID_i} \quad (7)$$

where QW is the total weight of one node in quadrants with different levels. W_{QID_i} is the weight of node located in Quadrant QID_i.

Suppose two nodes are located in Quadrant 1 and Quadrant 2 respectively, and the *QW* values of the two nodes are equal. According to FQMM, there is a higher probability that more rescuers are allocated in Quadrant 1 than in Quadrant 2. In that case, it is better to choose next hop nodes in Quadrant 1 than in Quadrant 2, because the probability of connecting to the destination node is higher. As a result, the priority of each quadrant is as follows: Quadrant 1 > Quadrant 2 > Quadrant 4 > Quadrant 3. When the *QW* values of the nodes are equal, we can choose the node in the high priority quadrant as the next hop node.

4.2.3. FQMMBP design

In this section, we propose FQMMBP protocol based on FQMM. Routing discovery and routing maintenance process are illustrated in Figure 10 and Figure 11 respectively.

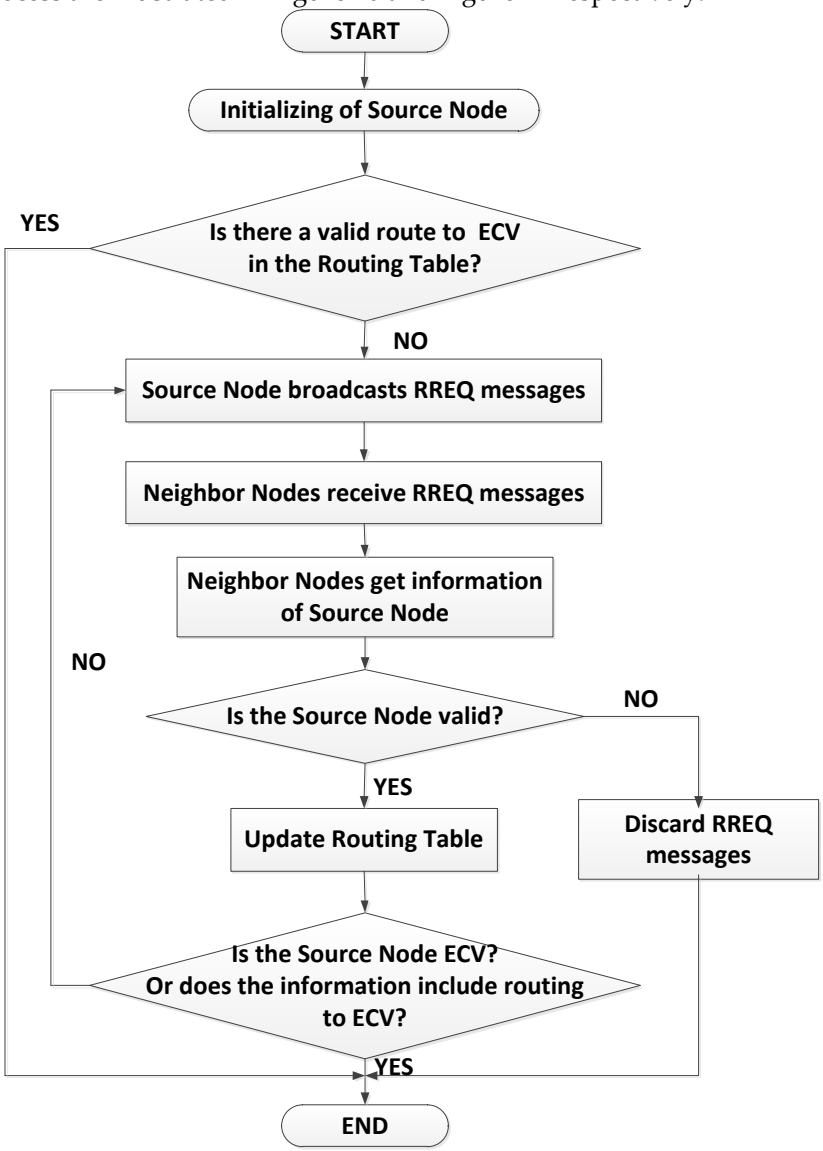

Figure 10. Routing establishment process for FQMMBP

As shown in Figure 10, source node (denoted as N_S) checks whether there is a route to ECV. If there is no route to ECV, the node broadcasts RREQ message to its neighbor node (denoted as N_N). After receiving the message, N_N first checks whether N_S is a valid node. If N_S is invalid, N_N discards the received RREQ message; otherwise, N_N updates the routing table and finds out whether there is routing information to ECV. If there is no route to ECV, N_N forwards the received RREQ message. Repeat the broadcasting and checking process until one or more valid routes to the ECV are found.

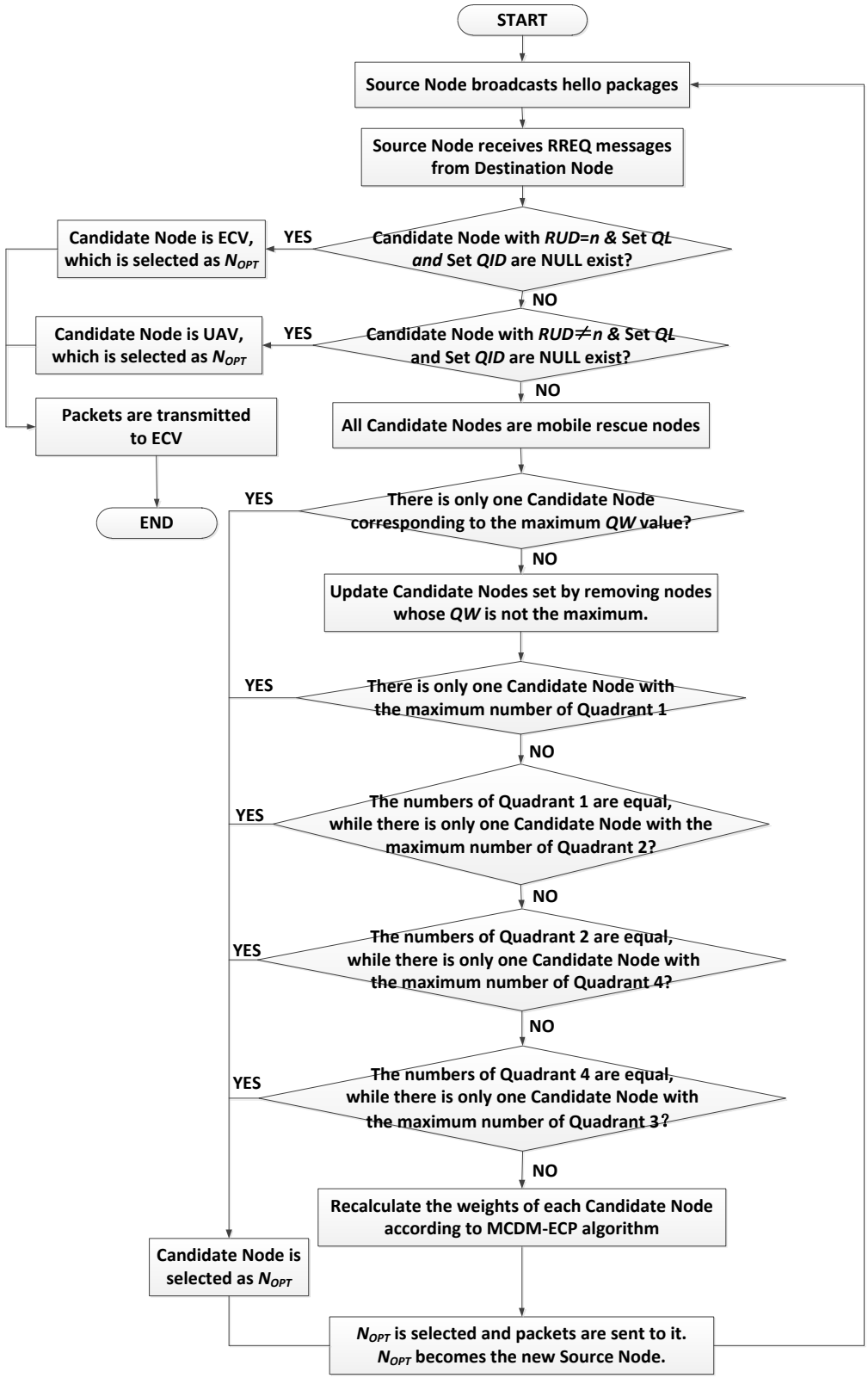

Figure 11. Routing maintenance process for FQMMBP

As shown in Figure 11, source node (denoted as *Ns*) sends *hello* packets to the candidate nodes within its coverage by broadcasting, and receives RREQ replies from them. *Ns* determines whether there is a RREQ reply sent by ECV by checking whether there is a candidate node with *RUD=n* and both *QL* and *QID* are empty in RREQ reply. If there is an ECV within the coverage of *Ns*, data packets are directly transmitted to ECV which is the destination of the communication, and communication ends. If there is no ECV within the coverage of *Ns*, then *Ns* determines whether there is a RREQ reply sent by fixed UAV by checking whether there is a candidate node with

$RUD \neq n$ and both QL and QID are empty in RREQ reply. If there is an UAV within the coverage of N_S, data packets are forwarded to UAV, and UAV forwarded data packets to its neighbor. Repeat this process until ECV is founded, finally communication ends. If there are neither ECVs nor UAVs in the candidate nodes, we compare QW values. If there is only one candidate node corresponding to the maximum QW value, then this node is the optimal next hop node (denoted as N_{OPT}). N_{OPT} becomes a new source node N_S, and then it sends the *hello* packets to repeat the process. If the maximum QW value corresponds to more than one candidate nodes, we should update candidate nodes set by removing nodes whose QW is not the maximum. After that, we select N_{OPT} from the new set according to the following **Cases**:

Case 1: There is only one candidate node with the maximum number of Quadrant 1. This node is selected as N_{OPT}.

Case 2: The numbers of Quadrant 1 are equal, while there is only one candidate node with the maximum number of Quadrant 2. This node is selected as N_{OPT}.

Case 3: The numbers of Quadrant 2 are equal, while there is only one candidate node with the maximum number of Quadrant 4. This node is selected as N_{OPT}.

Case 4: The numbers of Quadrant 4 are equal, while there is only one candidate node with the maximum number of Quadrant 3. This node is selected as N_{OPT}.

Case 5: Recalculate the weights of each candidate node according to MCDM-ECP algorithm [20] and then select N_{OPT}.

The description of FQMMBP routing maintenance process is completed.

5. Experiment

In this section we present the network level performance evaluation and simulations results of the proposed routing protocol based on NS-2 platform. For comparison, with the respect to each relevant class of routing protocols, we selected the pertinent protocols which are the most widely used (e.g., AODV[17]、DSR[18] 、DSDV[18]).

5.1. Simulation Setup

The simulation environment is a $10km \times 10km$ earthquake disaster area, in which the epicenter of the most severely affected area is $6km \times 4km$. There are 48 mobile rescue nodes, two fixed UAVs and one ECV. The simulation setup and respective parameters are detailed in Table 3.

Table 3. Simulation Parameters.

Parameters	Values
Number of mobile rescue nodes (M)	48
Fixed communication nodes（ECV included）	3
Simulation time span	600s
Area of earthquake affected regions	$10km$*$10km$
a_1	$6km$
b_1	$4km$

5.2. Simulation Results

In this section, four routing protocols, e.g., FQMMBP, AODV, DSDV and DSR are analyzed from the perspective of package delivery rate (PDR), end-to-end delay (delay) and overhead.

5.2.1. Package Delivery Rate

Figure 12 shows the performance of Package Delivery Rate (PDR) for the different studied protocols. Our proposed FQMMBP achieves the best performance with nearly 91.24% of average PDR while the other three protocols with about 80% of average PDR. This proves that FQMMBP improves communication efficiency and stabilizes communication link status in a long period of time. DSDV achieves the worst performance with 79.23% of average PDR mainly due to the mobility of communication nodes. DSDV is a proactive protocol and each node maintains a route

table. In the emergency rescue scenario, routing tables are dynamic due to the mobility of rescuers, thus causing the cost of maintaining routing tables. The superiority of FQMMBP over other three routing protocols is mainly attributed to FQMM mobility model. In each disaster area under this model, the distribution of rescue mobile nodes tends to be uniform, which increases the probability that each node can find the appropriate next-hop node to forward data, and ensures the integrity and reliability of communication link. Packets are likely to be delivered successfully in such distributions of nodes.

PDR performances of the four compared protocols are almost the same before 150s, that is because all nodes are concentrated in the central area with *RUD*=1 at the beginning of simulation. At this point, the distributions of nodes in the four protocols are similar, and each node has not started to disperse or move to the next area according to the mobility model. As time goes on, the PDR of each protocol decreases gradually. This is because when the nodes complete the rescue tasks in the central area, they will spread to the next peripheral rectangular ring, resulting in the scattered distribution of nodes and the increase of distance between nodes, so the stability of communication link becomes poor. On the contrary, mobile nodes are evenly distributed and close to ECV under our proposed FQMMBP, which improves PDR.

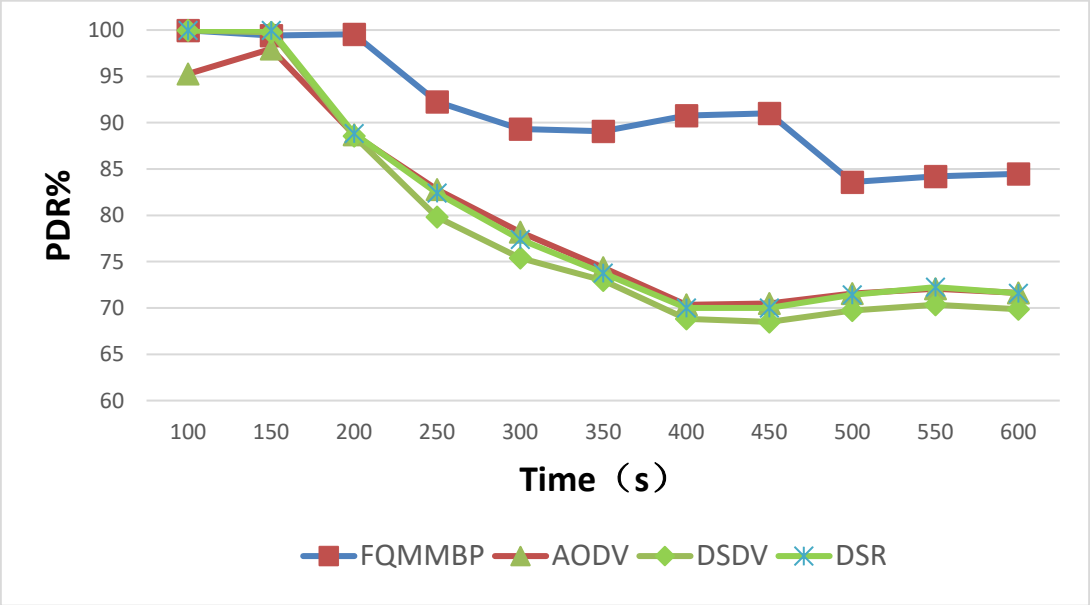

Figure 12. Comparison of packet delivery rate (PDR) for four protocols

5.2.2. End-to-end delay

Figure 13 shows the performance of End-to-end delay (delay) for the different studied protocols. In terms of delay, FQMMBP is significantly lower than other classical routing protocols. During the simulation, the average delay decreased from 1.44s of DSR to 0.55s of FQMMBP, which proves the significant improvement of communication performance. This is because in each rescue area, the distribution of mobile nodes tends to be uniform under FQMMBP, which increases the probability that each node can find the next hop node to communicate with. Within the coverage of each relay node, the existence probability of candidate next hop node increases, which shortens the time to find the candidate next hop node as well as the time to transmit data to ECV.

Performances of four compared protocols are almost the same before 150s. This is because at the beginning of the simulation, all nodes are concentrated in the central rectangular area with the most serious seismic intensity. At this time, the distributions of nodes are relatively centralized and similar, and the nodes have not started to disperse and move according to their respective mobility models, so the performance differences of the four protocols are not significant. As time goes on, the delay of each protocol increases gradually, because all nodes will spread to the next peripheral rectangular ring when the rescue tasks in the central area are completed. The dispersion of nodes

leads to the increase of distance between nodes; therefore, it takes longer for relay nodes to find the appropriate next hop nodes as the decreasing numbers of candidate next hop nodes. The distribution of mobile nodes is more uniform under the proposed FQMMBP, which shortens the delay.

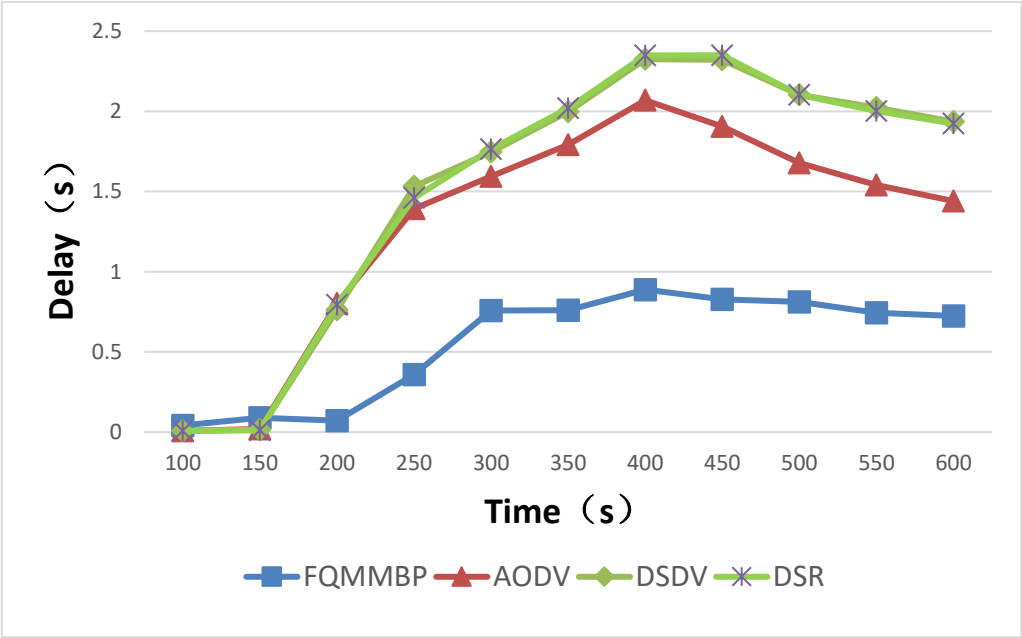

Figure 13. Comparison of delay for four protocols

In the period of 200s to 300s, the delay increases obviously as the nodes spread to the next area around when they finish the rescue tasks in the central area. The node distribution changes from the original rectangular centralized to the rectangular ring decentralized, so the node distribution density becomes low, which increases the delay. After 300s, the delay tends to be stable. This is because there is no significant change in the distributions of nodes when they move from the area with *RUD*=2 to the areas with *RUD*>2. In that case, the delay tends to be stable because of the little impact on FQMMBP.

5.2.3. Overhead

Figure 14 shows the performance of overhead for the different studied protocols.

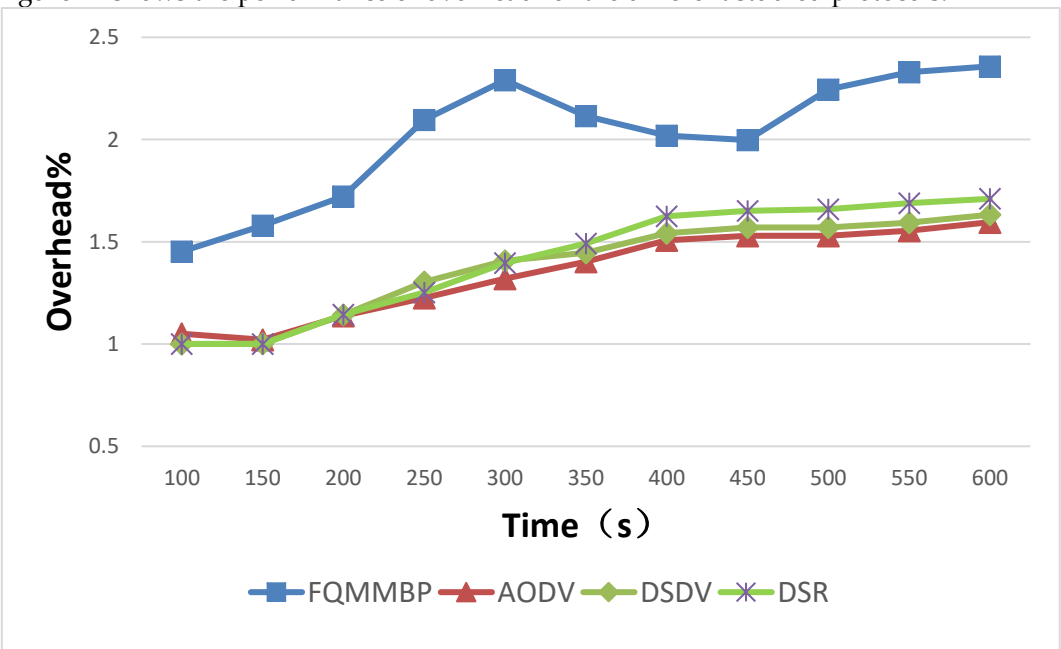

Figure 14. Comparison of overhead for four protocols

In terms of overhead, FQMMBP is significantly larger than other classical routing protocols. That is because four new fields (*RUD*, *QL*, *QID* and *QW*) are added to RREQ message. Furthermore, the dispersion of nodes increases the number of forwarding packets, which also contributes to the increase of overhead. The data transmission overhead of AODV, DSDV and DSR protocols increases with time, while FQMMBP meets the same rule from 100s to 300s. However, the overhead of FQMMBP is decreasing between 300s and 450s, that is because before 300s, the rescue nodes are distributed centrally, and they are far away from the destination nodes. Most of the data transmissions rely on fixed relay nodes for forwarding, so the overhead is increasing. In the period of 300s to 450s, the distribution of rescue nodes is scattered, and the average distance between rescue nodes and destination nodes is close. In that case, the number of data forwarding is reduced, so the overhead is reduced. After 450s, the distribution of rescue nodes is more scattered than before, and the data communication between nodes relies on multi-hop forwarding, which makes the data transmission overhead increasing. After 600 seconds, the overhead of FQMMBP can be controlled within 2.5%. Although the performance of FQMMBP in overhead is not as good as the other three protocols, it is worthwhile for the emergency rescue.

6. Conclusions

Protocols for post-earthquake emergency communication network are different with traditional ones because of the heterogeneity and dynamicity of the network. After the earthquake, Rescue urgency degree is related to in affected areas. In this paper, we first divide the whole disaster area into several regions with different *RUD* values according to catastrophic intensity. A four-quadrant mobility model for rescuers based on *RUD* is proposed. Under this mobility model, we propose the FQMMBP protocol for emergency communication network, which improved the RREQ message by adding four new fields: *RUD*, *QL*, *QID* and *QW*. Simulation results show that FQMMBP is superior to traditional routing protocols (AODV, DSDV and DSR) in performances of PDR and Delay. Although FQMMBP performs not as good as the other three protocols in performance of overhead, it is worthwhile for the emergency rescue.

List of Abbreviations

ECN- Emergency communication network.
FQMM- Four-quadrant mobility model.
FQMMBP- FQMM-based protocol.
AODV- Ad hoc On-Demand Distance Vector Routing.
DSDV- Destination-Sequenced Distance-Vector Routing.
DSR- Dynamic Source Routing.
PDR- Package delivery rate.
DCHS- Deterministic cluster head selection.
RUD- Rescue urgency degree, which is inversely proportional to the seismic intensity value in this area. The closer the area is to the epicenter, the lower the value of RUD is, which means the disaster is serious and the priority of rescue is high; Otherwise, the opposite. When RUD = 1, the epicenter disaster area is a rectangle; When RUD > 1, the disaster areas are rectangle rings that expands outwards in turn.
ECV- Emergency communication vehicle.
BS- Base station.
UAV- Unmanned Aerial Vehicle.
PIE- Portable individual equipment.
QL- Quadrant Level, which is the number of times the quadrant divided.
QID- Quadrant ID.
RT- Number of Rescue Tasks.
NRA- Number of Rescuers Allocated.
GPS- Global Positioning System.
RREQ- Routing request.

Competing interests

The authors declare that they have no competing interests.

Author's contributions

All authors contribute equally.

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Author details

[1]Shanghai Earthquake Administration, No.87 Lanxi Rd, Shanghai, China.

[2]The College of Information, Mechanical, and Electrical Engineering, Shanghai Normal University, No. 100 Guilin Rd, Shanghai, China.

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Figures

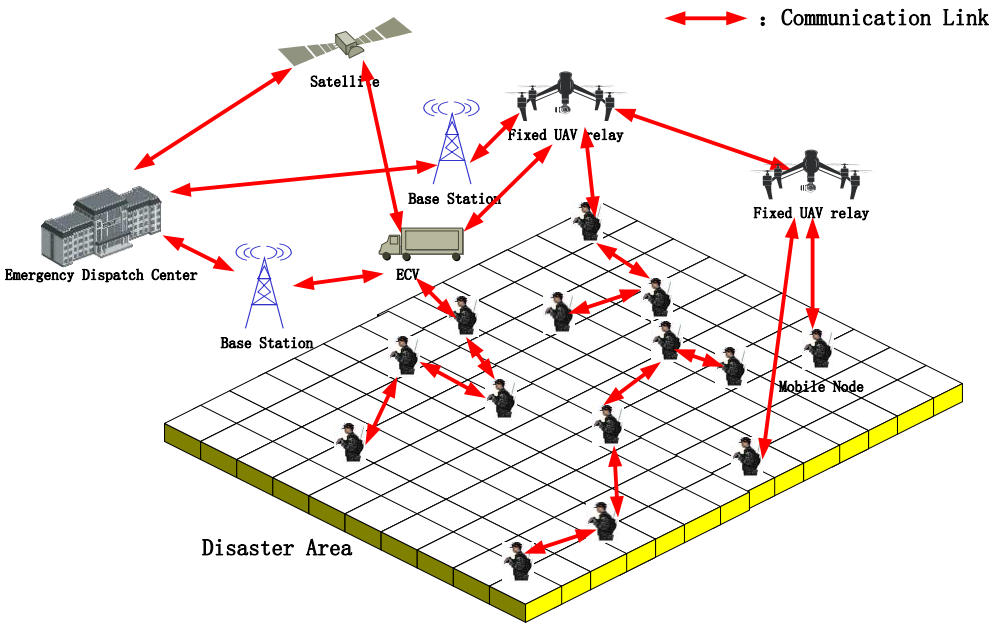


Figure 1. An example of post-earthquake ECN

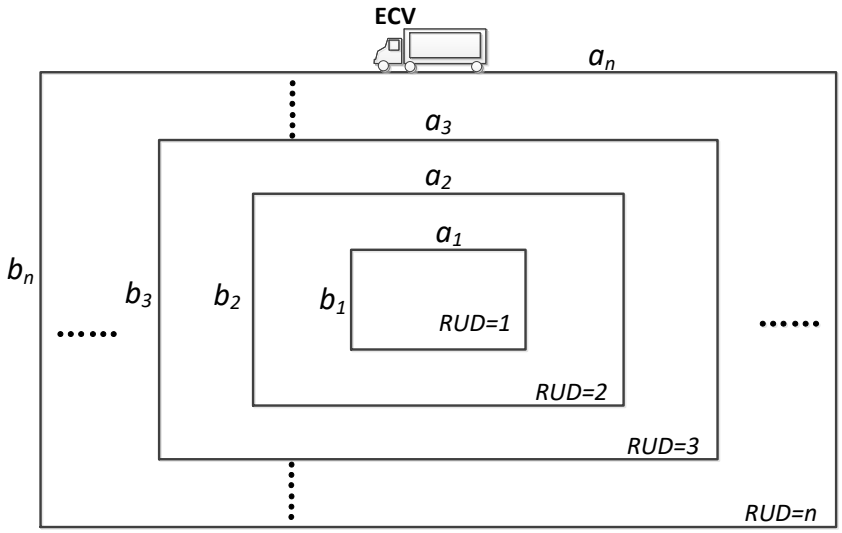


Figure 2. Disaster area division according to *RUD*

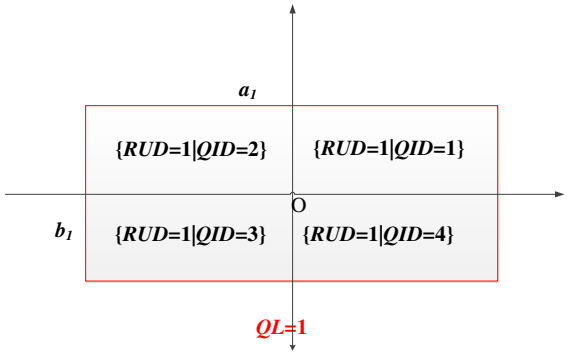


Figure 3. Disaster area with *RUD*=1 is divided into 4 quadrants for the first time (*QL*=1)

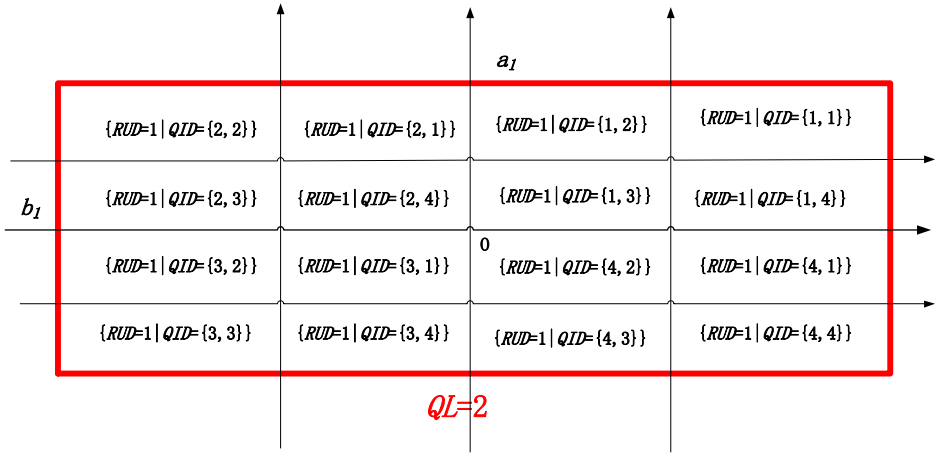


Figure 4. Disaster area with *RUD*=1 is divided into 16 quadrants for the second time (*QL*=2)

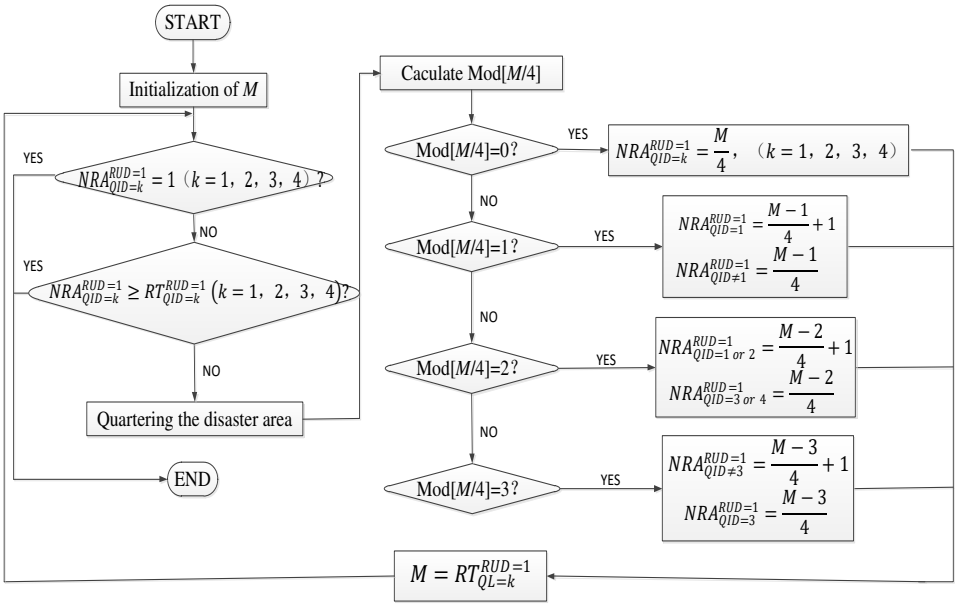
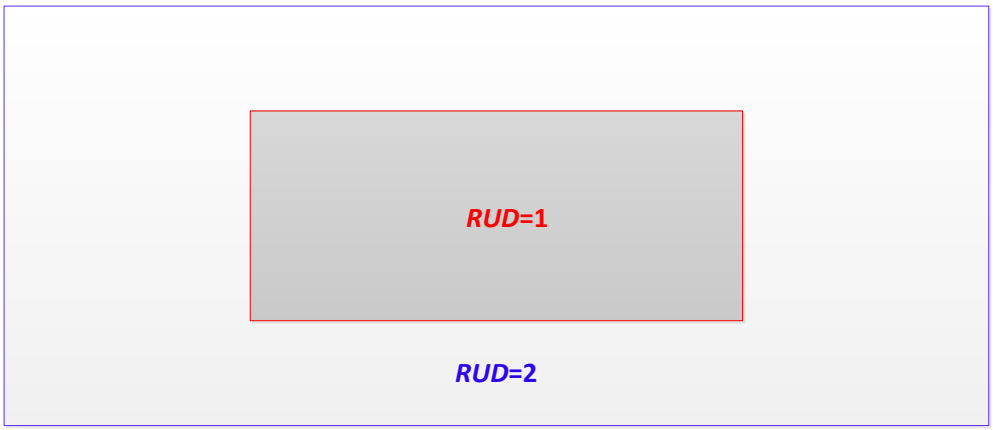
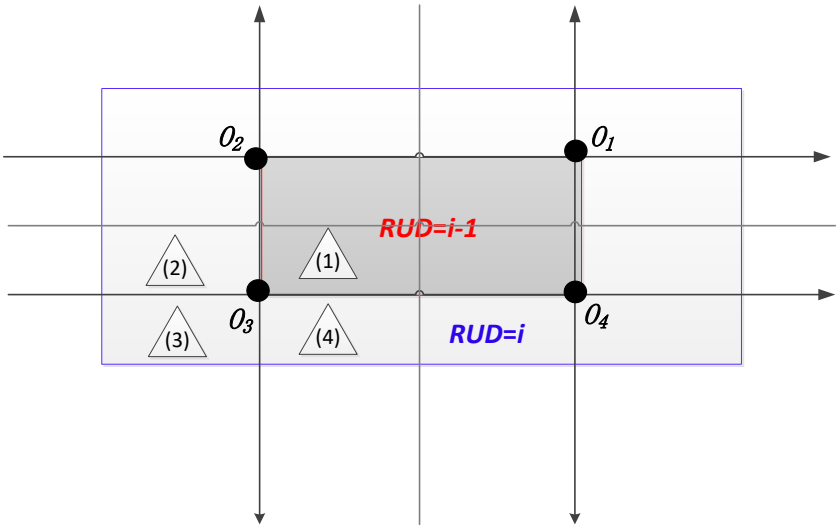


Figure 5. Allocation process of rescue nodes in disaster area with *RUD*=1



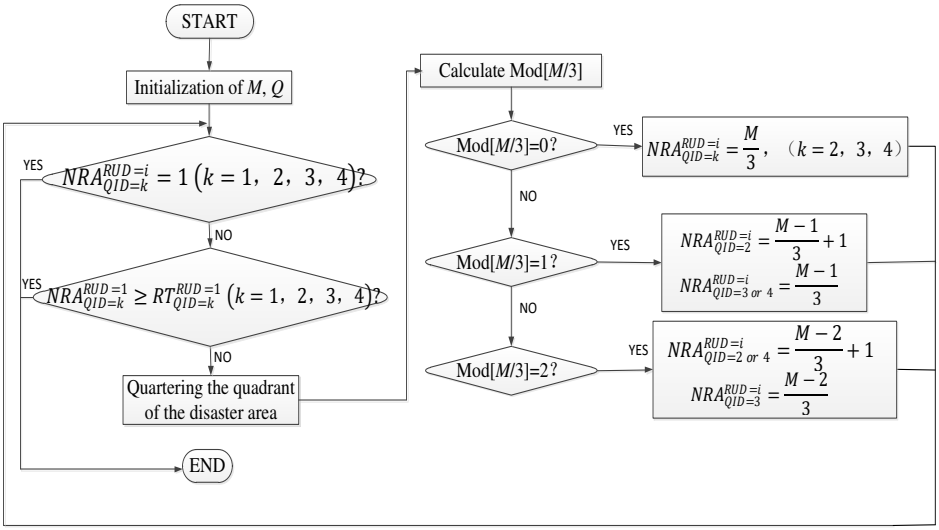
658

659 **Figure 6.** Rectangular ring with *RUD*>1



660

661 **Figure 7.** Disaster area with *RUD*>1 is divided into 12 quadrants for the first time (*QL*=1)



662

663 **Figure 8.** Allocation process of rescue nodes in disaster area with *RUD*>1

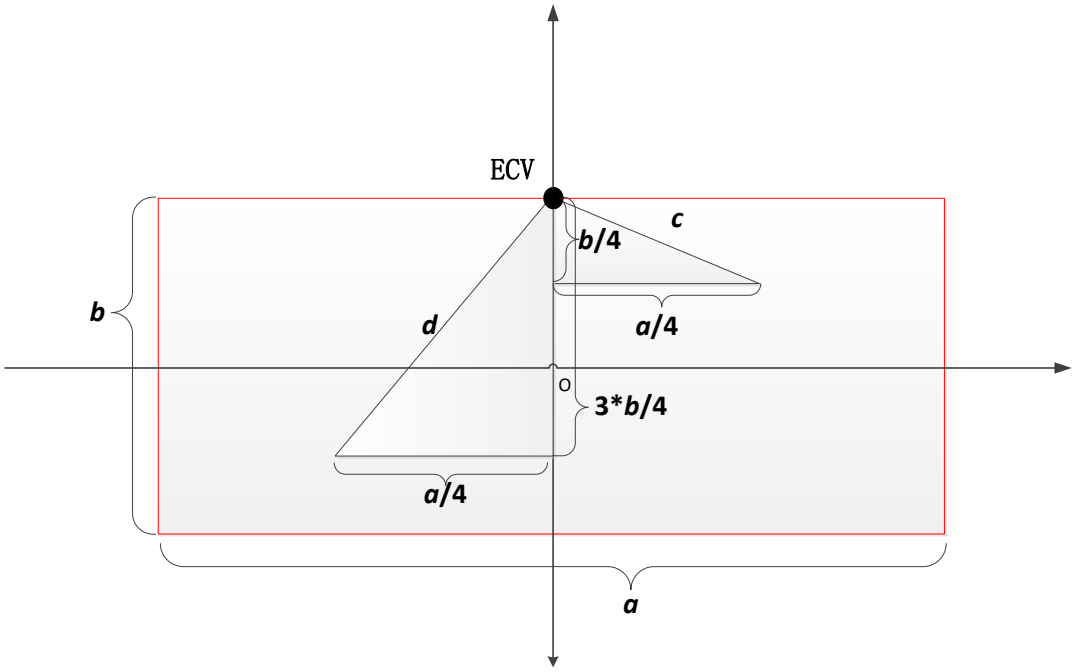


Figure 9. Calculate the weight of each quadrant according to the distance from quadrant center to ECV

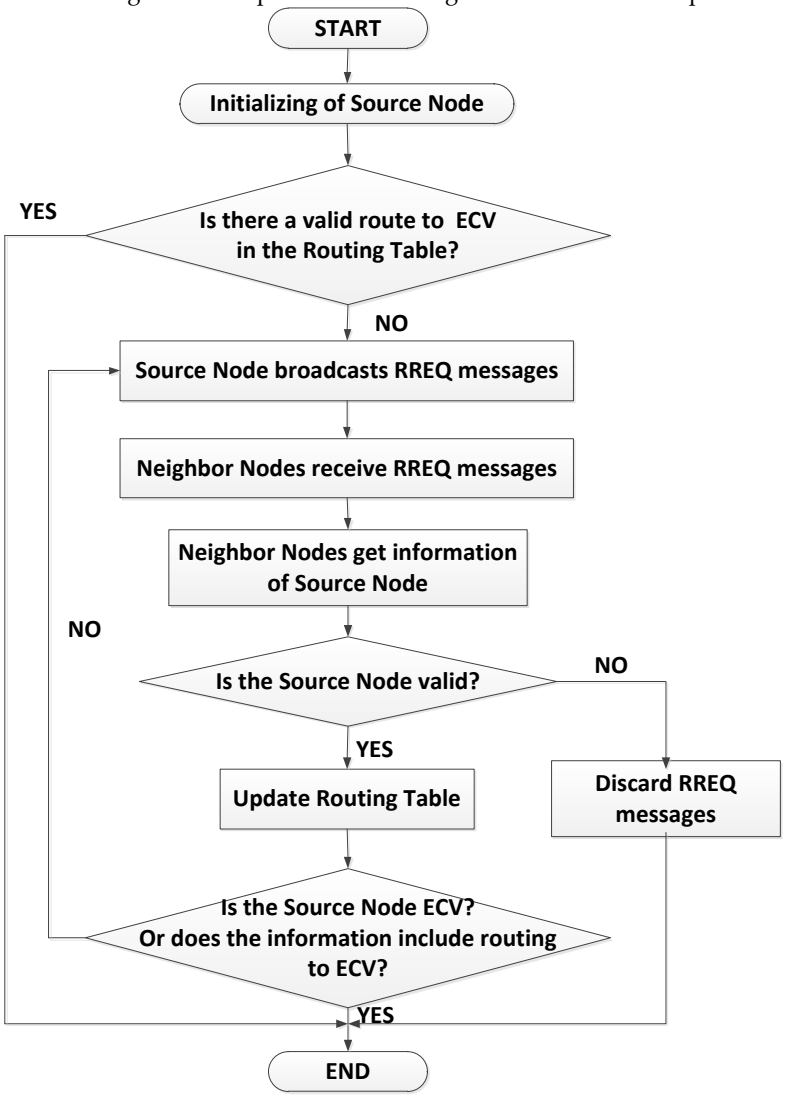


Figure 10. Routing establishment process for FQMMBP

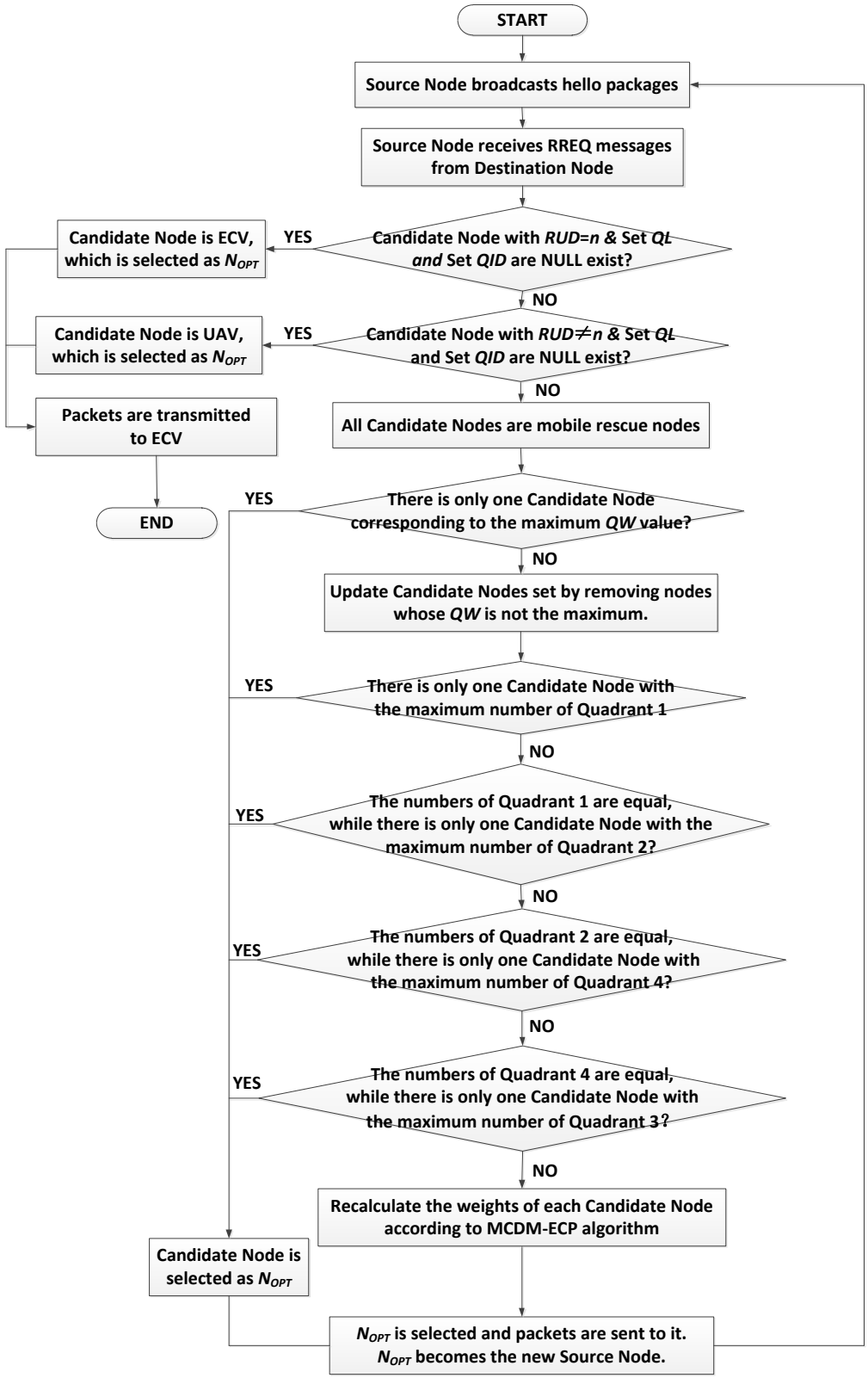


Figure 11. Routing maintenance process for FQMMBP

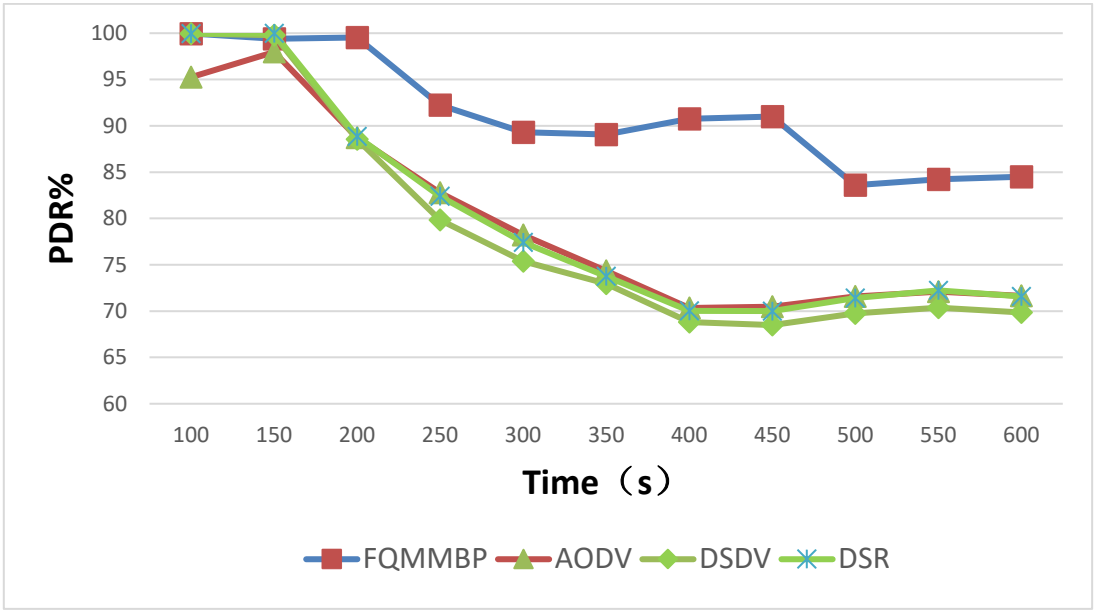


Figure 12. Comparison of packet delivery rate (PDR) for four protocols

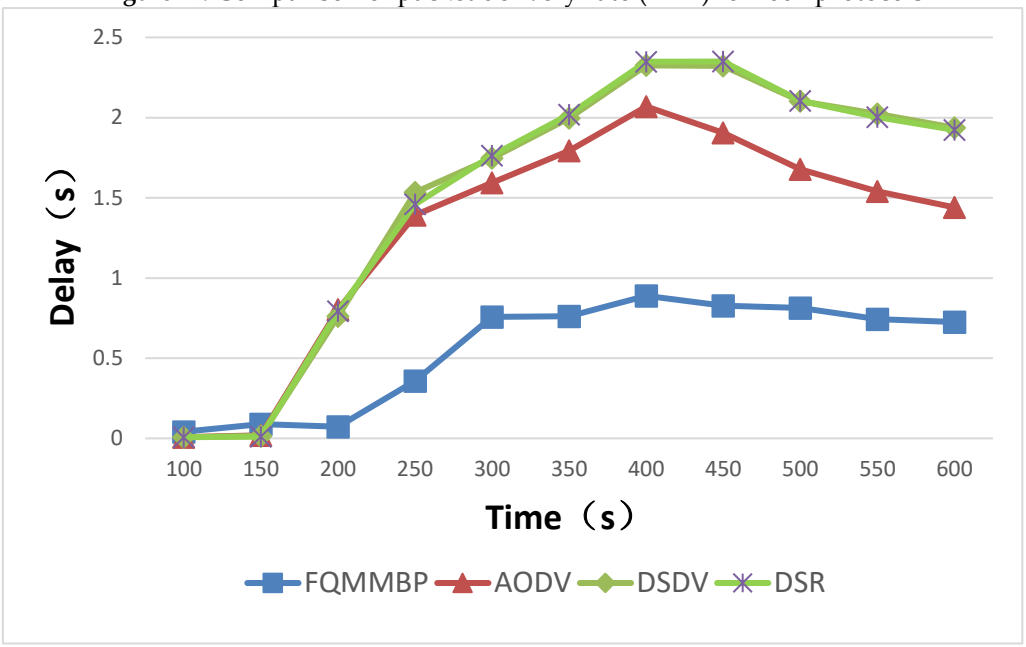


Figure 13. Comparison of delay for four protocols

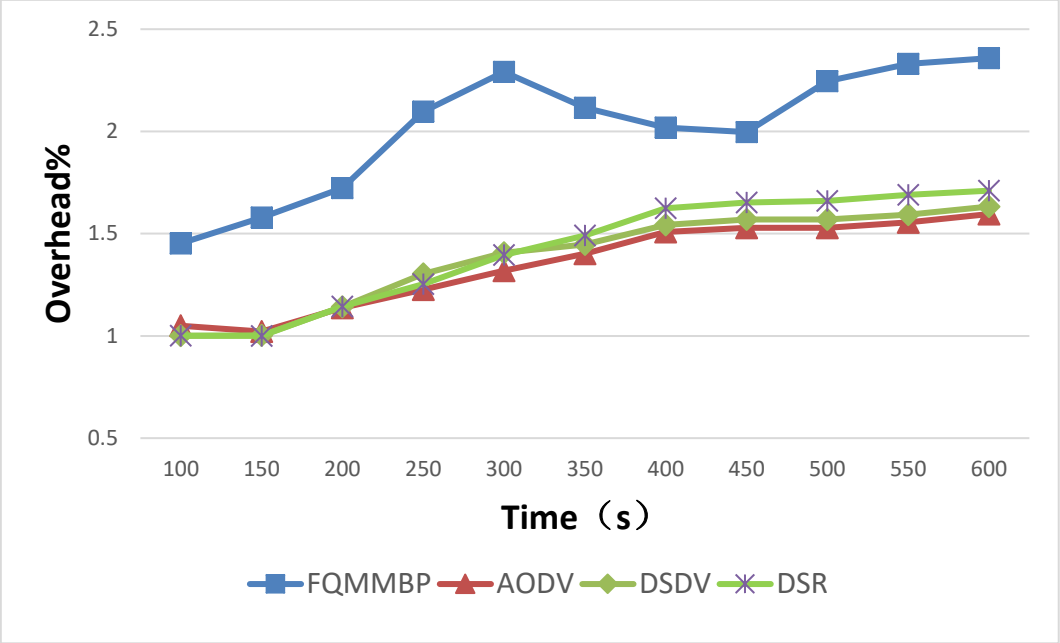


Figure 14. Comparison of overhead for four protocols

Tables

Table 1. Parameter definition and description

Parameters	Description
RUD	Rescue Urgency Degree, which is inversely proportional to the seismic intensity value in this area. The closer the area is to the epicenter, the lower the value of *RUD* is, which means the disaster is serious and the priority of rescue is high; Otherwise, the opposite. When *RUD* = 1, the epicenter disaster area is a rectangle; When *RUD* > 1, the disaster areas are rectangle rings that expands outwards in turn.
a_i	Length of area where *RUD*=*i*.
b_i	Width of area where *RUD*=*i*.
QL	Quadrant Level, which is the number of times the quadrant divided.
QID	Quadrant ID.
RT	Number of Rescue Tasks.
NRA	Number of Rescuers Allocated.
M	Number of mobile nodes.

Table 2. The improved RREQ data format.

Type	Flags					Reserved	Hop Count
	J	R	G	D	U		
RREQ ID							
Destination IP Address							
Destination Sequence Number							
Source IP Address							

Source Sequence Number
RUD
QL
QID
QW

685

686 **Table 3.** Simulation Parameters.

Parameters	**Values**
Number of mobile rescue nodes (*M*)	48
Fixed communication nodes（ECV included）	3
Simulation time span	600s
Area of earthquake affected regions	10*km**10*km*
a_1	6*km*
b_1	4*km*

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Figures

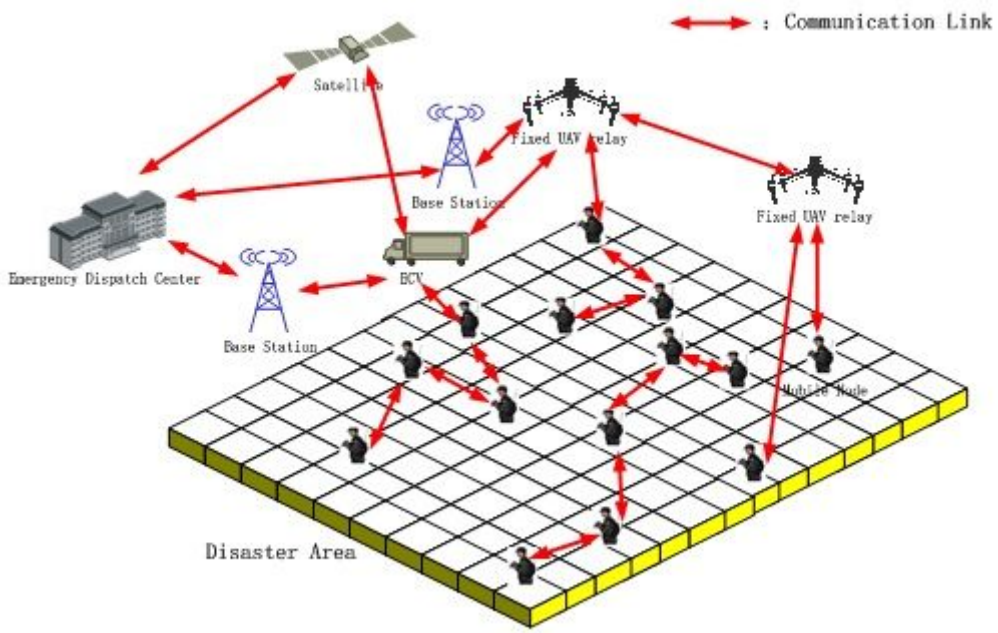


Figure 1

An example of post-earthquake ECN

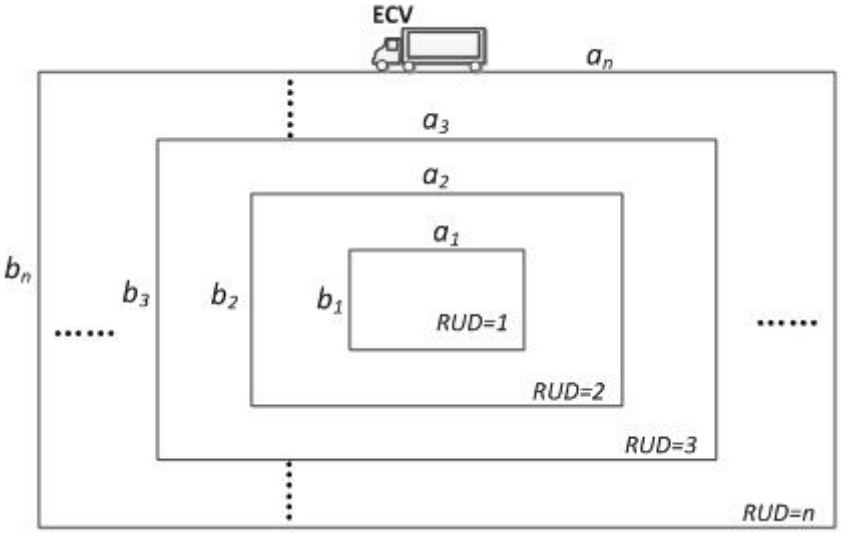


Figure 2

Disaster area division according to RUD

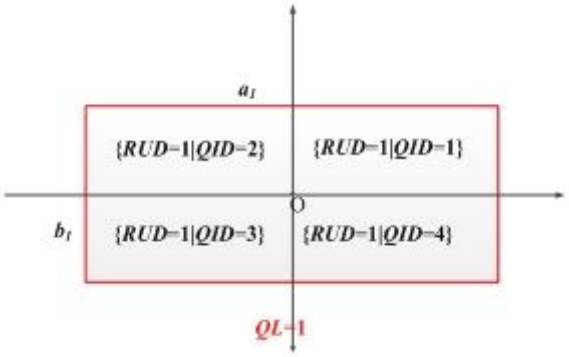
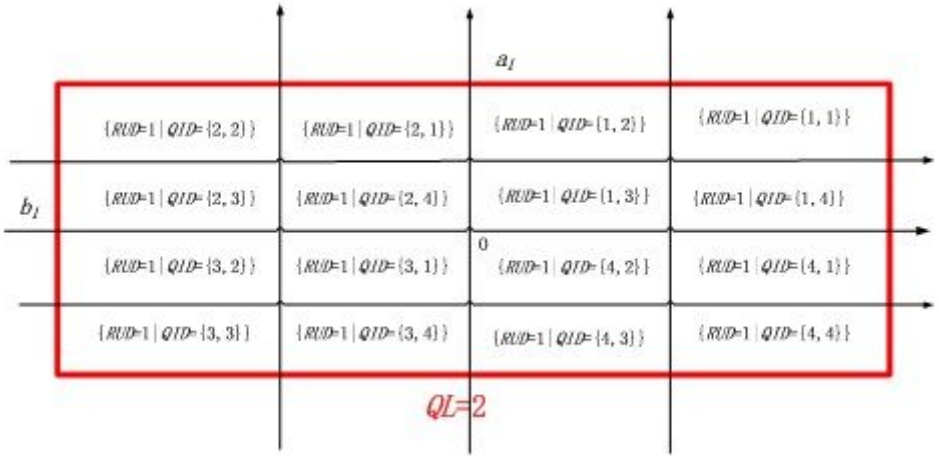


Figure 3

Disaster area with RUD=1is divided into 4 quadrants for the first time (QL=1)



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Disaster area with RUD=1is divided into 16 quadrants for the second time (QL=2)

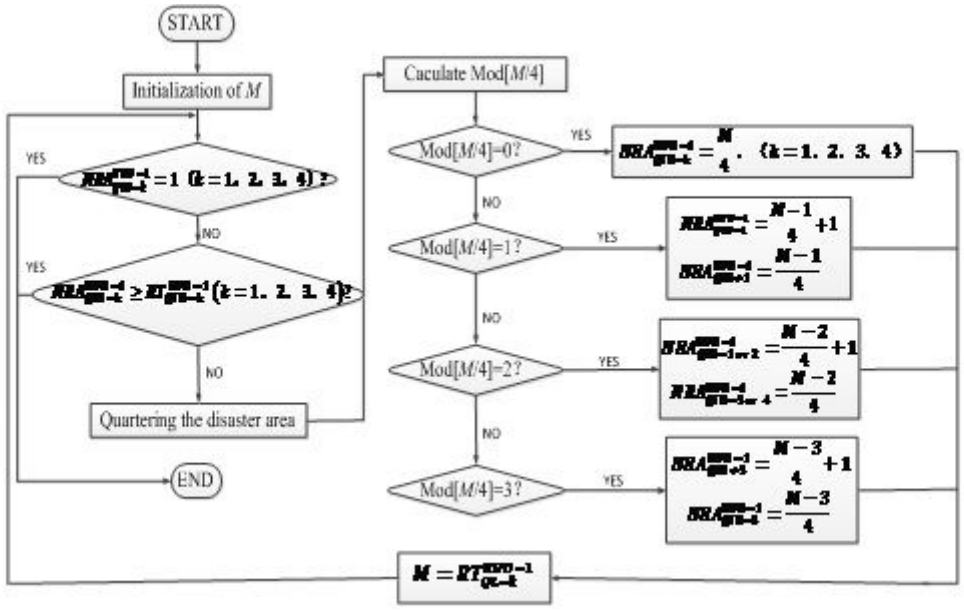


Figure 5

Allocation process of rescue nodes in disaster area withRUD=1

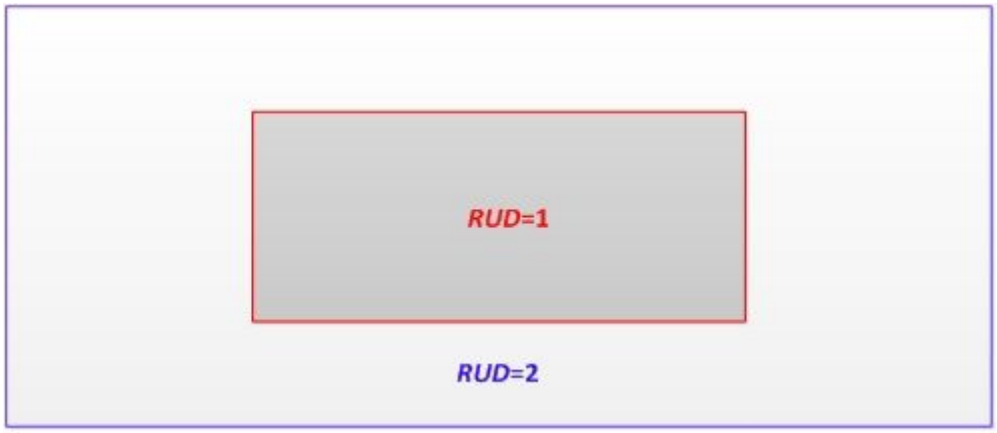


Figure 6

Rectangular ring with RUD>1

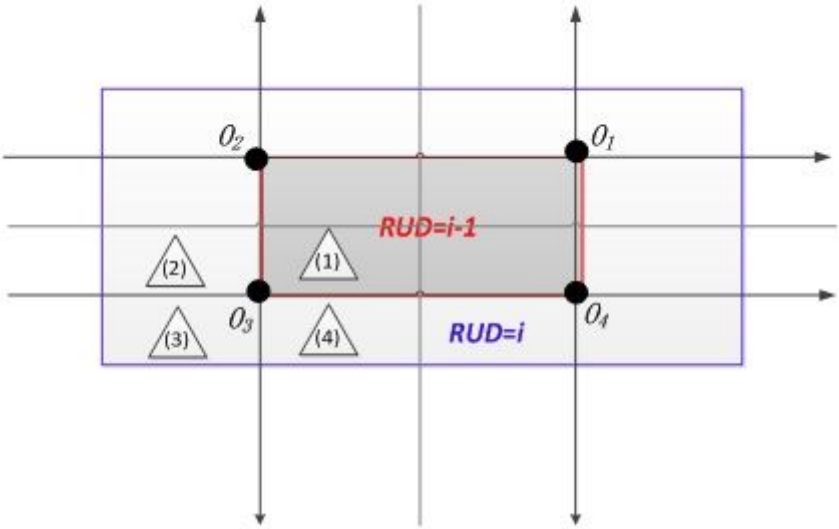


Figure 7

Disaster area with RUD>1is divided into 12 quadrants for the first time (QL=1)

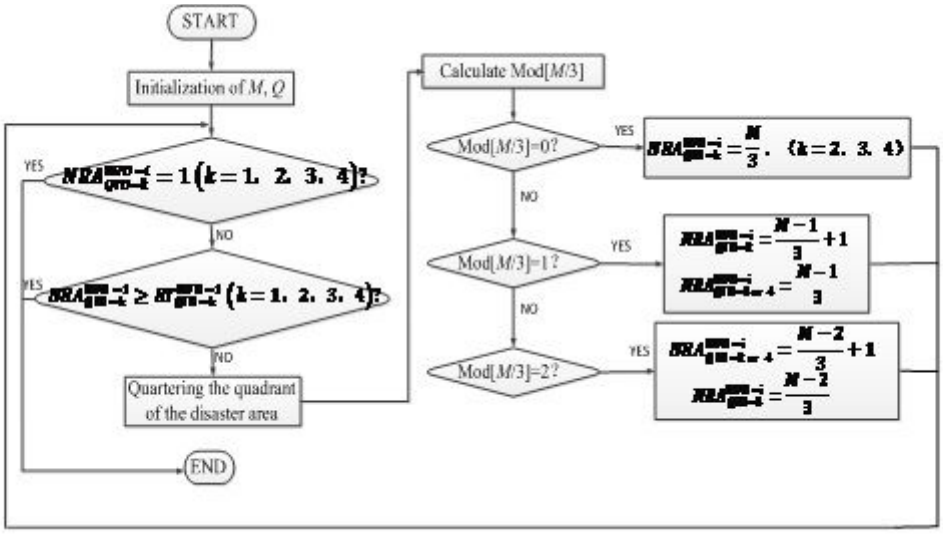
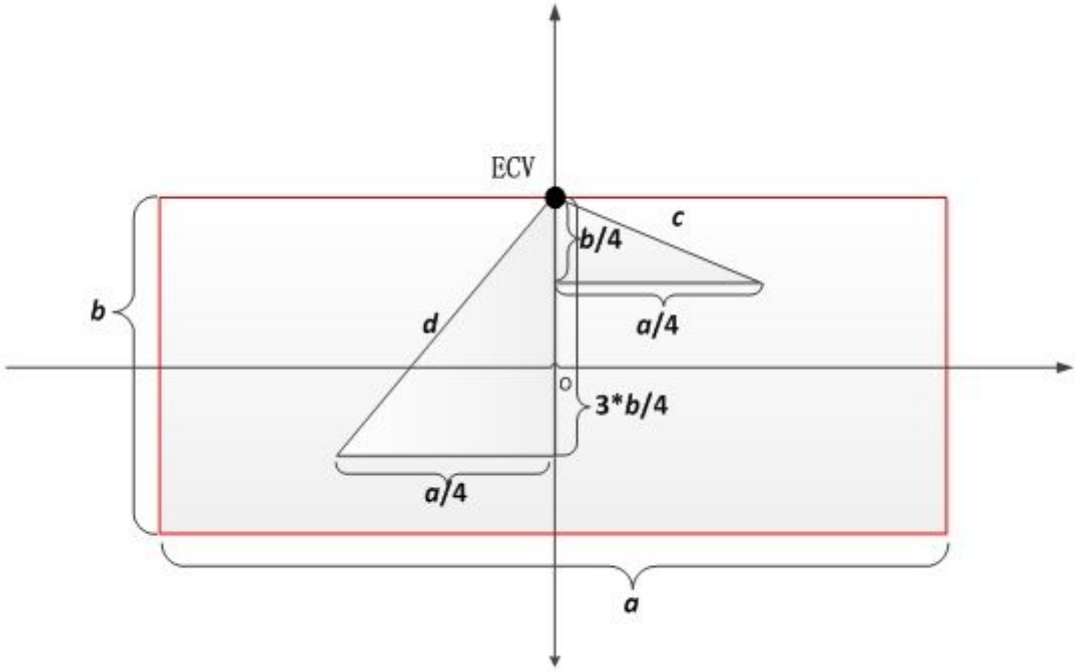


Figure 8

Allocation process of rescue nodes in disaster area withRUD>1



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Calculate the weight of each quadrant according to the distance from quadrant center to ECV

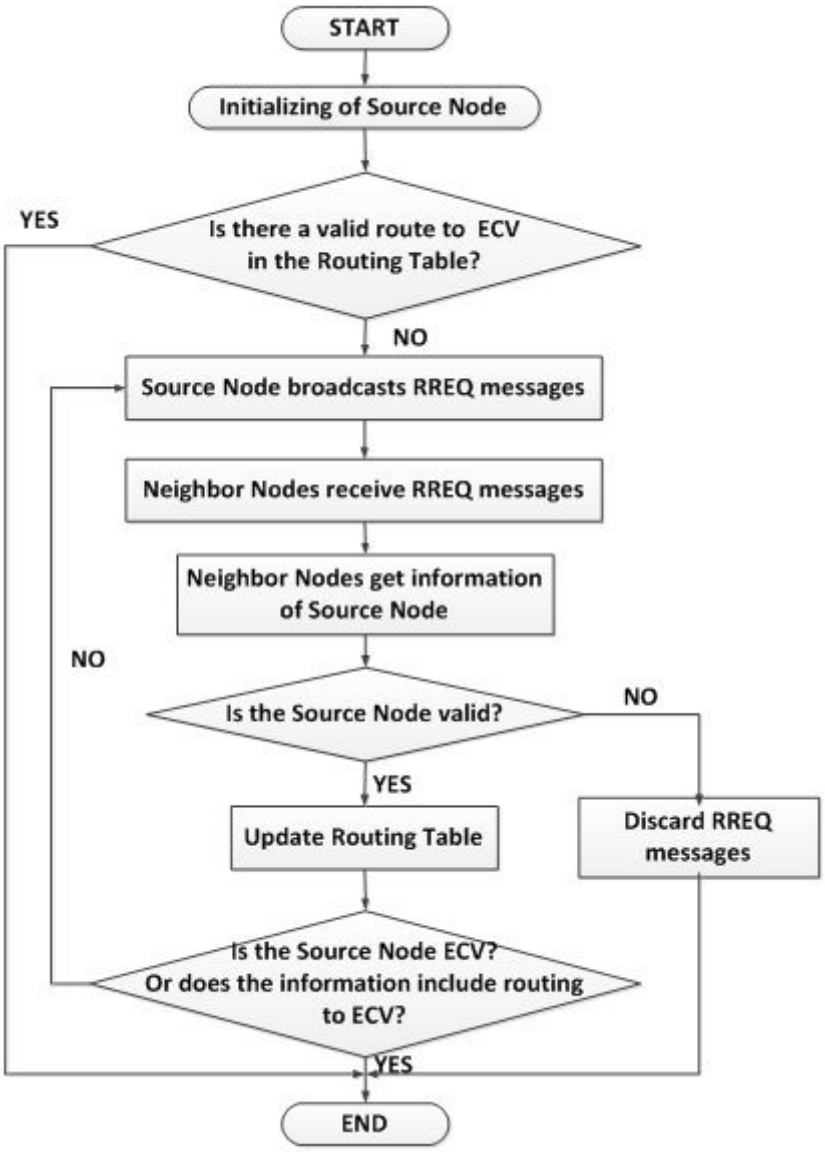

Figure 10

Routing establishment process for FQMMBP

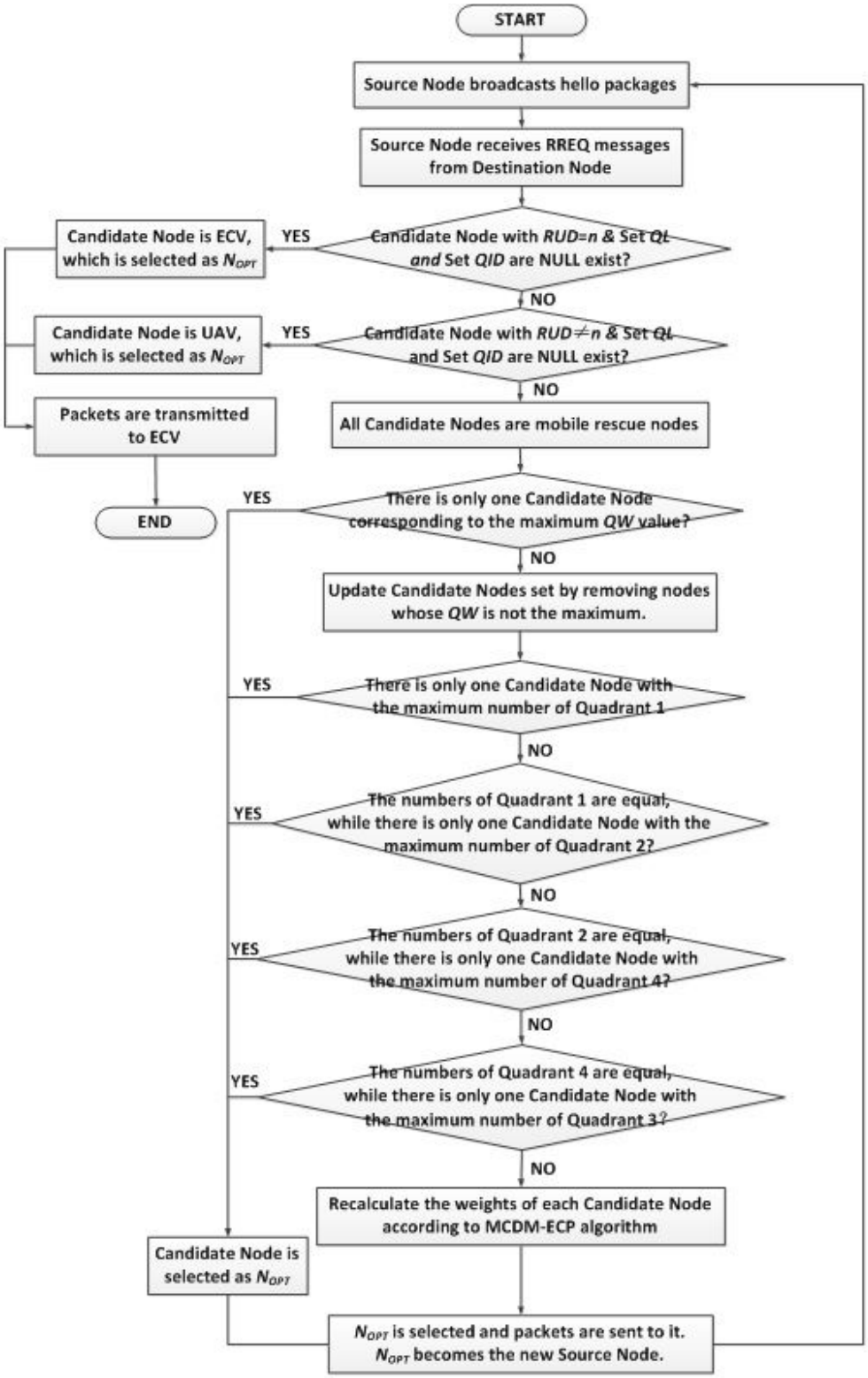

Figure 11

Routing maintenance process for FQMMBP

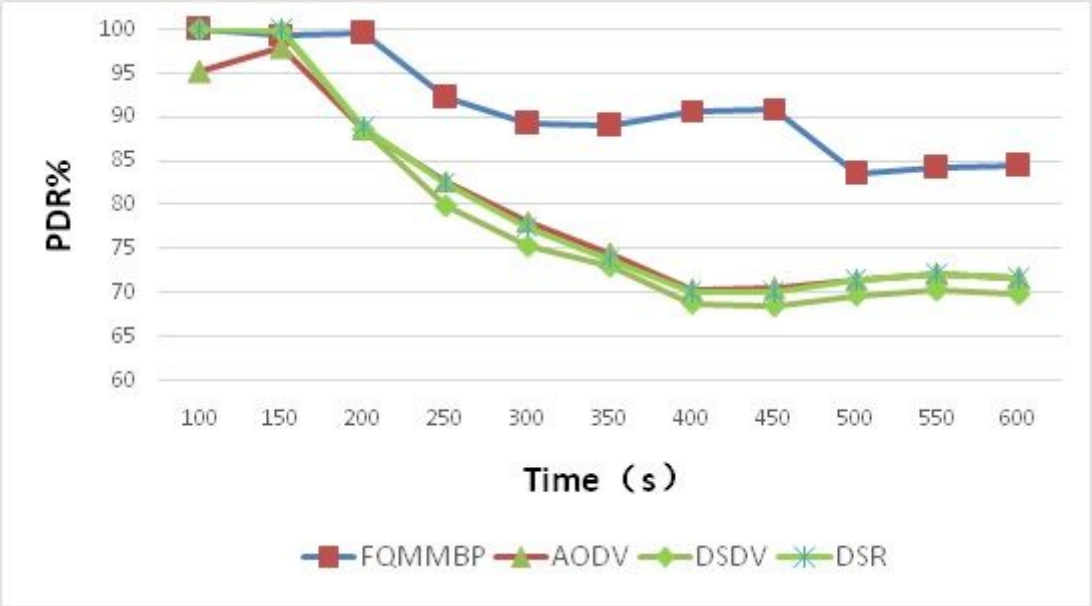

Figure 12

Comparison of packet delivery rate (PDR)for four protocols

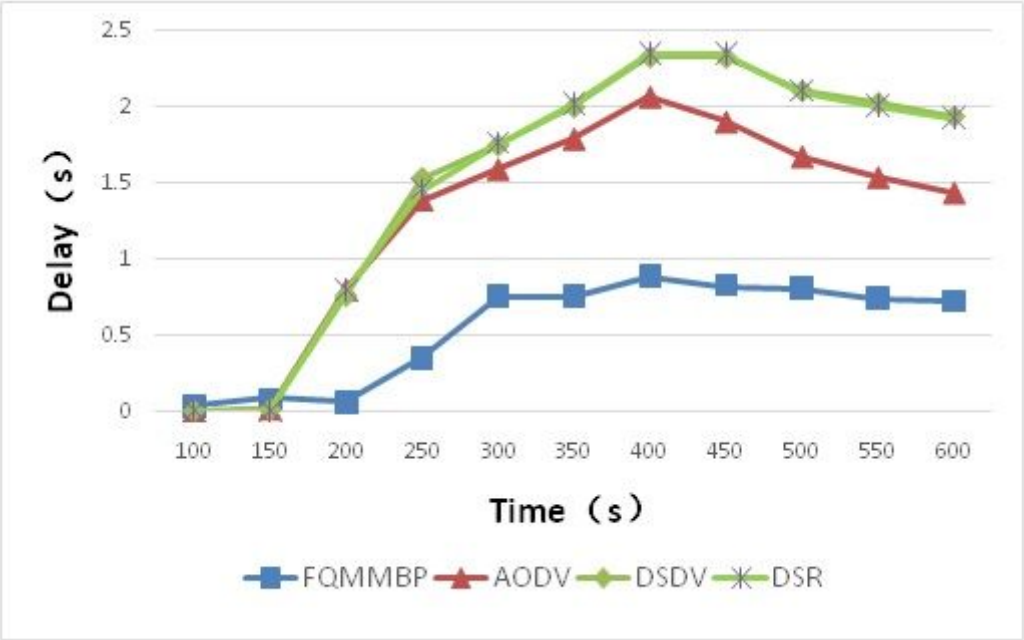

Figure 13

Comparison of delay for four protocols

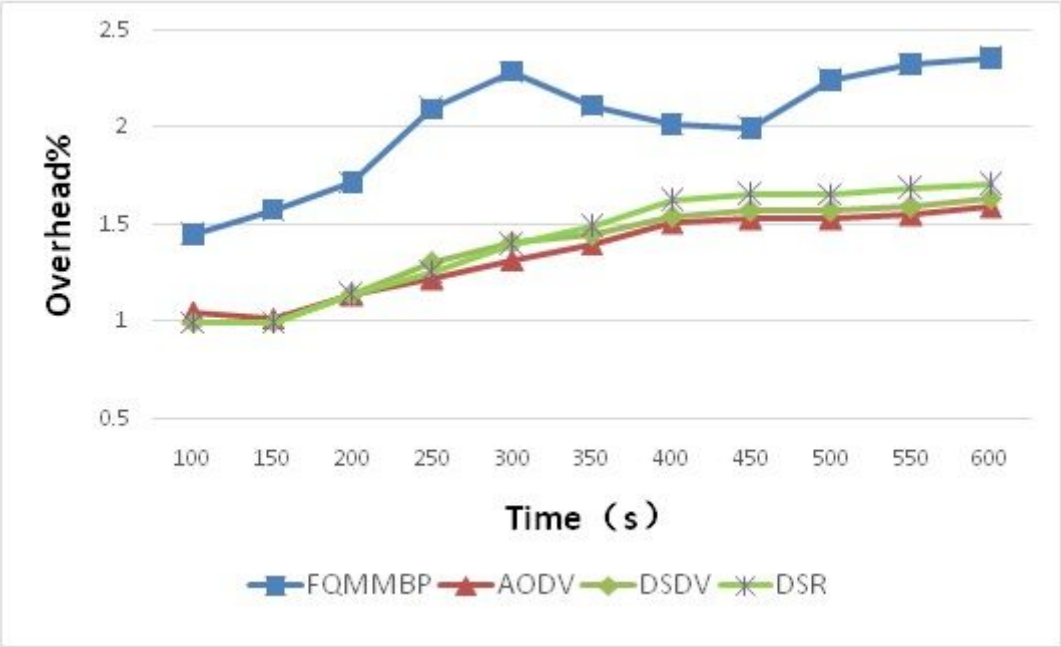

Figure 14

Comparison of overheadfor four protocols

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