Master's Thesis
석사 학위논문

Cooperative Spatial Retreat Technique of Net-Drones under Communication Failure

Jin-Hyeok Kang (강 진 혁 姜 珍 赫)

Department of Information and Communication Engineering

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Co-advisor : Professor Hongsoo Choi

by

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Information and Communication Engineering. The study was conducted in accordance with Code of Research Ethics[1].

Nov. 30. 2016

Approved by

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[1] Declaration of Ethical Conduct in Research: we, as a graduate student of DGIST, hereby declare that we have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. We affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

Cooperative Spatial Retreat Technique of Net-Drones under Communication Failure

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Accepted in partial fulfillment of the requirements for the degree of Master of Science

Nov. 30. 2016

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ABSTRACT

Drones are broadening their scope into various applications such as agriculture, package delivery, broadcast, leisure, and rescue, among others. However, drones must overcome some technical issues to become widely usable. One such issue is resilience in communication. Current drones are normally remote-controlled. This makes it hard to successfully complete missions without continuous communication.

When drones experience communication failure due to interference, non-line-of-sight, or jamming, one possible solution is spatial retreat to evacuate them from the communication failure area. Previous spatial retreat schemes only move the drones in random directions. In doing so, the accuracy and efficiency of the moving distance is not adequate. In this paper, we propose a novel retreat technique that can enable resilient networking. Our approach is called *cooperative spatial retreat* (CSR). We have found it to significantly outperform existing schemes by exploiting telemetry communication modules.

Keywords: Aerial networks, Drones, UAV, UAS, Spatial retreat, Topologic management

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I. INTRODUCTION

Networking has become an essential element of daily life, especially because of rapid advances in the Internet of Things (IoT) [1] and smartphones. Thus, people and devices are perpetually connected to networks and rely on them for routine functions. Consequently, it is critically important to provide a reliable network infrastructure for various kinds of applications in the cyber-physical systems [2, 3]. However, emergency networking, such as disaster areas, requires extensive time for service providers to deploy additional infrastructure.

If network service is sufficient in disaster areas, people can notify their families about their safety or and location in case they become isolated in a collapsed structure. Even if a person is unconscious, adequate network service can enable venders to find his or her approximate location via localization schemes. Hence, a reconstructed network would help to rescue many people in disaster areas, so there is a social demand for immediate improvements to network service.

Currently, network service venders temporarily extend networks by using communication relay vehicles. This is a common and sufficient solution when roads are clear and intact. However, in large-scale disasters such as earthquakes, tsunamis, and typhoons, we cannot realistically expect the roads to be clear enough for communication relay vehicles to move into disaster areas. Therefore, drones are a promising solution for significantly reducing deployment times. A drone, normally known as an unmanned aerial vehicle (UAV) or unmanned aerial system (UAS), is an aircraft controlled remotely or autonomously, without a human pilot. Aerial networks, or net-drones [4], can be used to reconstruct network infrastructure. Fig. 1.1 depicts an example of net-drone connectivity.

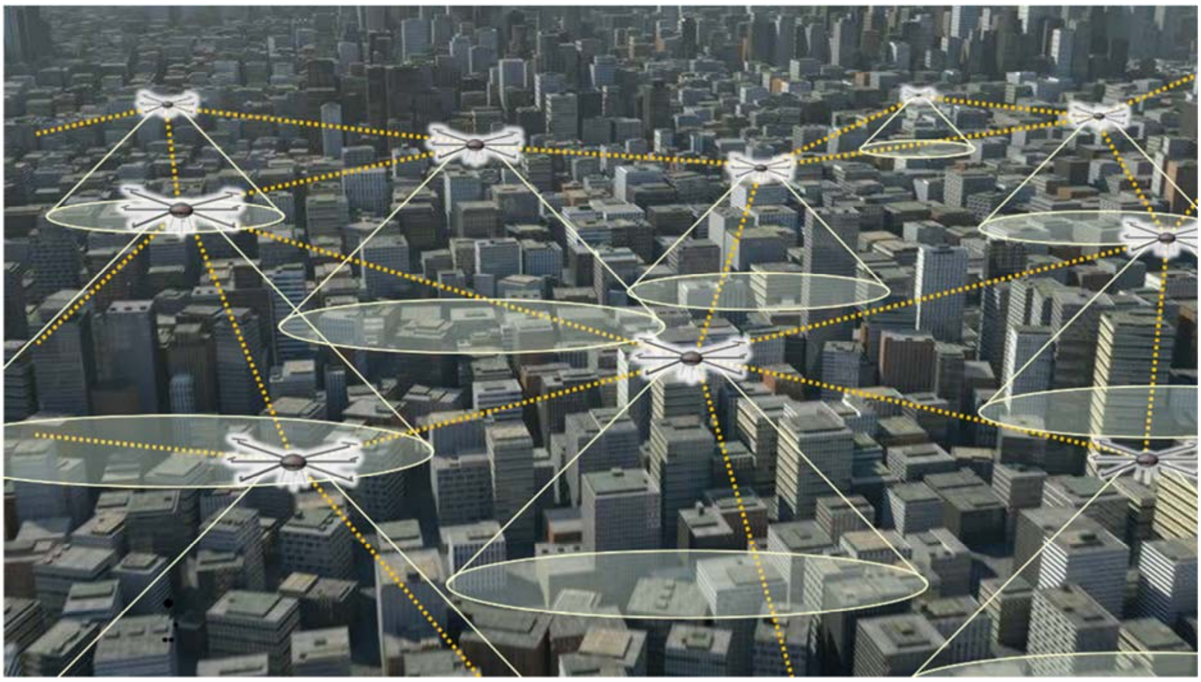


Figure 1.1. Illustration of net-drone connectivity.

The most important advantage of drones is their uninhibited mobility. Conventional vehicles, such as cars and trains can only move in two dimensions; whereas, net-drones exploit the mobility of drones in three-dimensional space. This allows drones to maneuver over obstacles like traffic jams. Thus, drones may be a promising replacement for delivery and emergency response vehicles; however, certain technical limitations need to be solved.

First, drone consumes large amounts of energy by flying through the air. This also makes it difficult to provide network service over long distances. Second, commercially available drones are lightweight aerial vehicles, which makes them vulnerable to wind pressure, especially in poor weather conditions. Third, drones are remotely or autonomously controlled, so they need continuous wireless communication. In addition, net-drones may suffer from communication failure due to interference, non-line-of-sight, or jamming. In this paper, we mainly focus on continuous wireless communication in order to overcome communication failures in net-drones, To solve this problem, previous studies have proposed channel surfing [5] and spatial retreat [6]. Channel surfing operates similarly to Bluetooth. However, it only partially copes with some communication failure problems in net-drones. However, this solution has an upper limit in overcoming most communication failure problems. Hence, we consider spatial retreat as a more comprehensive solution to these problems.

A major limitation of the spatial retreat technique is efficiency. Conventional spatial retreat has no information to signal a drone to evacuate, so it signals a drone to evacuate from a communication failure area in a random direction. This functionality may prompt the drone to move a long distance to evacuate. Doing so increases energy consumption and decreases mission duration. In addition, this tactic cannot compensate for rapidly changing failure areas.

To overcome this limitation, we propose a novel spatial retreat mechanism that can provide resilient networking service. Our prototypical method is called *cooperative spatial retreat* (CSR). This technique exploits additional telemetry communication modules and significantly outperforms existing schemes. The CSR scheme collects locational information from drones in communication failure areas and calculates a central point of communication failure.

The remainder of this paper is organized as follows. In Section II, we provide background information on drones, net-drones, channel surfing, and spatial retreat. In Section III, we describe the proposed spatial retreat algorithm of CSR. We describe the performance of this CSR algorithm through simulation and compare the results to those using the conventional spatial retreat technique in terms of ideal moving distance via the nearest outside drone in Section IV. Finally, we explain our conclusions and propose ideas for future research in Section V.

II. BACKGROUND

2.1 Net-Drone

Currently, the drone industry is rapidly growing as a promising technology to improve delivery and emergency response, among other applications. Another name for a drone is *unmanned aerial vehicle* (UAV) or *unmanned aerial system* (UAS). In the first half of the 20th century, drones were developed for military purposes, specifically to perform scouting, monitoring, and bombing missions. Recently, many global companies have invested in R&D for commercial applications of drone technology. Already, drones used for broadcasting are very common, and most broadcasting companies operate drones for movies, narrative television, and sports matches.

Another use of drones is providing network infrastructure. In fact, Google and Facebook are trying provide Wi-Fi service for developing countries via drones as shown in Fig. 2.1.

Figure 2.1. Google Titan and Facebook Aquila.

Alternatively, the net-drone mainly provides network service for disaster areas. When disasters occur, significant parts of the network service infrastructure could be destroyed. In addition, consumption of network bandwidth rapidly increases in disaster areas as people contact their families and friends to update them regarding their safety status and request help.

Therefore, we need an immediate solution to this problem. However, reconstructing network infrastructure will require massive investment and long-term construction. Normally, network service venders temporarily expand bandwidth via relay vehicles, but these vehicles often cannot reach disaster areas. In this case, net-drones could replace relay vehicles and enhance emergency responses.

In the case of Titan and Aquila, a single drone covers a large area, while net-drones cover areas via drone fleets. Thus, net-drones require continuous connectivity to provide network service. A single, large drone is simple to manage; whereas, the advantage of drone fleets is flexibility. Accordingly, drone fleets could expand bandwidth to specific areas by using more drones.

2.2 Localization technique

Our CSR technique requires locational information. Hence, the reliability of localization is important for our scheme. GPS is a common technique to find a given location; however, it has several limitations, including its reliability. In non-line-of-sight (NLOS) situations such as indoor environments, GPS is unable to find specific locations. This could be a serious issue for drone fleets because controllers may lose command over drones. In this section, we present a general survey of effective solutions for complementing GPS for drone fleets. We categorize these localization techniques to find suitable options for drone fleets.

According to [7], localization techniques can be divided into two categories, centralized and decentralized, by nodal organization structure. Decentralized localization is further divided into two categories based on how to calculate locations between each node. These comprise range-based techniques and range-free techniques, as shown in Fig 2.2 [8].

Many localization techniques used in the field are range-based techniques. These can be divided in terms of their characteristics, such as angle and distance [9]. Range-free methods can also be divided via local hop counting [10]. Similarly, localization techniques can be divided into anchor/beacon-based or anchor/beacon-free; GPS-based or GPS-free; fine-grained or coarse-grained; and stationary or mobile sensor nodes, among others [11].

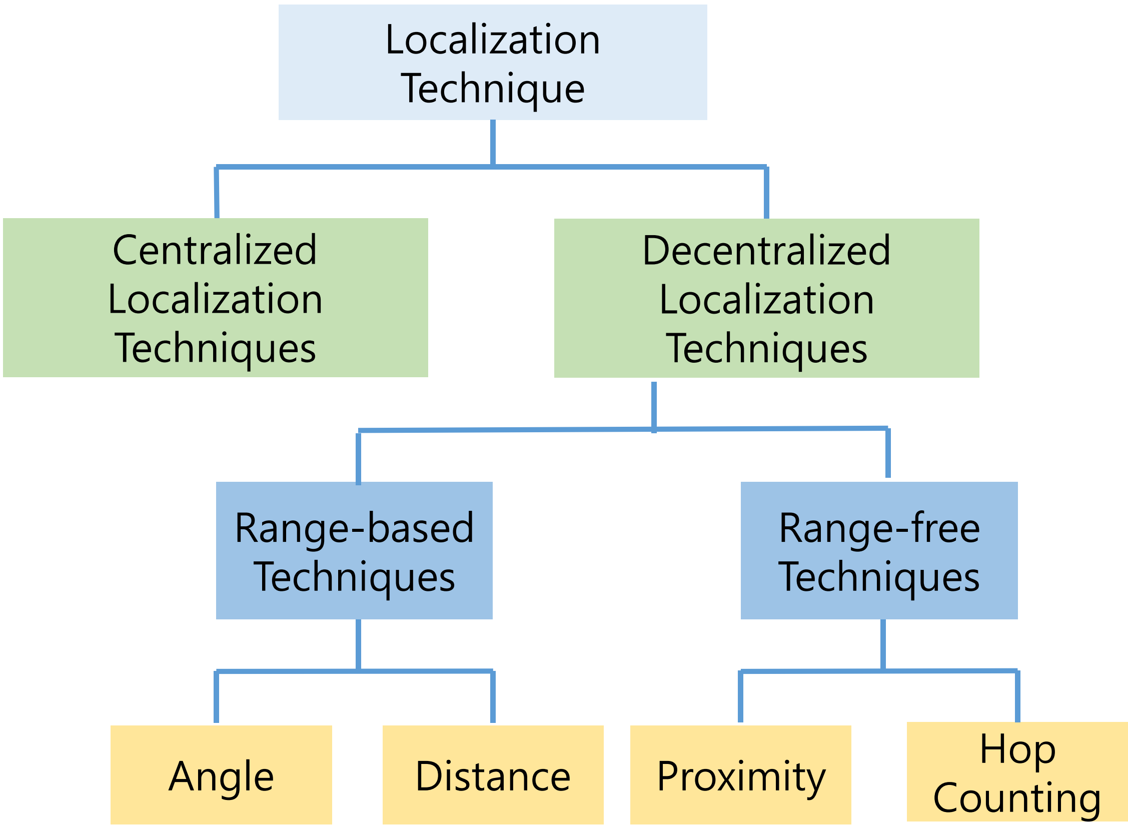


Figure 2.2. Sub-categories of the localization technique.

2.2.1 Centralized localization techniques

Centralized localization techniques transmit data to a central node, and the central node computes locational information about each individual node. In [12], the authors proposed a centralized technique, which is a method for estimating unknown node positions via convex optimization. This technique is based on connectivity-induced constraints. Conversely, MDS-MAP [13] is an algorithm that uses connectivity information through multidimensional scaling (MDS). MDS-MAP uses much less information and recovers more accurate maps of node location. These centralized localization techniques take advantage of the fact that nodes do not need expensive and sophisticated sensors such as GPS. Another advantage is that nodes do not require computational costs to calculate locations because the central node is responsible for all computation.

However, centralized localization techniques also have some disadvantages. For example, every node sends information to the central node, which requires significant communication costs, large bandwidth usage, and longer delays. In particular, the communication cost is a serious problem for drone fleets because drones are usually very sensitive to battery consumption. Frequent communication to the central node requires higher energy consumption. Consequently, centralized localization techniques may be unsuitable for drone fleets.

2.2.2 Decentralized localization techniques

Decentralized localization techniques transmit data to nearby nodes. As such, they do not rely on centralized computation, so they are able to determine their locations with limited communication. Thus, this approach is more suitable for drone fleets than centralized localization techniques. These techniques can be classified as range-based and range-free techniques.

Range-based localization techniques.

These techniques estimate the distance or angle between nodes, and find their location primarily by trilateration. These range-based techniques include most common localization techniques such as GPS, RSSI, TOA, TDOA, AOA, etc. Typically, more accurate range-based localization techniques are complex [10]. Mitigating this tradeoff is a critical issue.

Range-free localization techniques

Range-free localization is mainly classified into two categories, hop counting and local techniques. Importantly, the accuracy of the location estimate is usually smaller than that of range-based localization techniques. Local methods rely on a high nodal density. In particular, the centroid localization technique [14] is a range-free, proximity-based, coarse-grained localization technique that is suitable for small, energy efficient nodes without GPS. Functionally, it is based on the spherical radio propagation assumption. This technique finds a location by calculating the center of the locations of all nodes it can detect. Alternatively, the approximate point in triangulation (APIT) localization technique [15] utilizes an area-based, range-free localization approach. This technique requires a heterogeneous network of sensing devices to employ a novel, area-based approach to estimate location.

On the other hand, hop counting methods rely on flooding. The distance vector-hop (DV-Hop) localization technique [16] uses a similar mechanism to that of classical distance vector routing [17] to estimate the distance between unknown nodes and reference nodes, expressed as the product of the average hop distance and hop count [18].

III. COOPERATIVE SPATIAL RETREAT

3.1. Comparison of CSR to previous schemes

An existing strategy for escaping from a communication failure area is channel surfing [5], which is similar to frequency hopping. Another method is spatial retreat [6]. When drones experience interference, the conventional spatial retreat scheme enables drones to escape from the communication failure area in a random manner, as shown in Fig. 3.1. However, random escape is inefficient and may waste energy and deplete batteries through longer flying duration.

The key difference between the proposed CSR and conventional spatial retreat is that CSR further exploits information obtained from additional communication via assistance communication modules. In the conventional spatial retreat scheme, drones choose the evacuation direction in a random manner. Conversely, the proposed scheme exploits information from other drones to prompt a drone to move in a particular direction with a high probability of improving the channel condition. Additionally, conventional spatial retreat techniques was invented mainly for ground vehicles[19]. Accordingly, it only considers 2-dimensional movements. Hence, it is not fit for aerial vehicles such as drones.

Idea of CSR is mainly started from that if some drones are in the communication failure area, other direction should be safe location as shown in Fig 3.2.

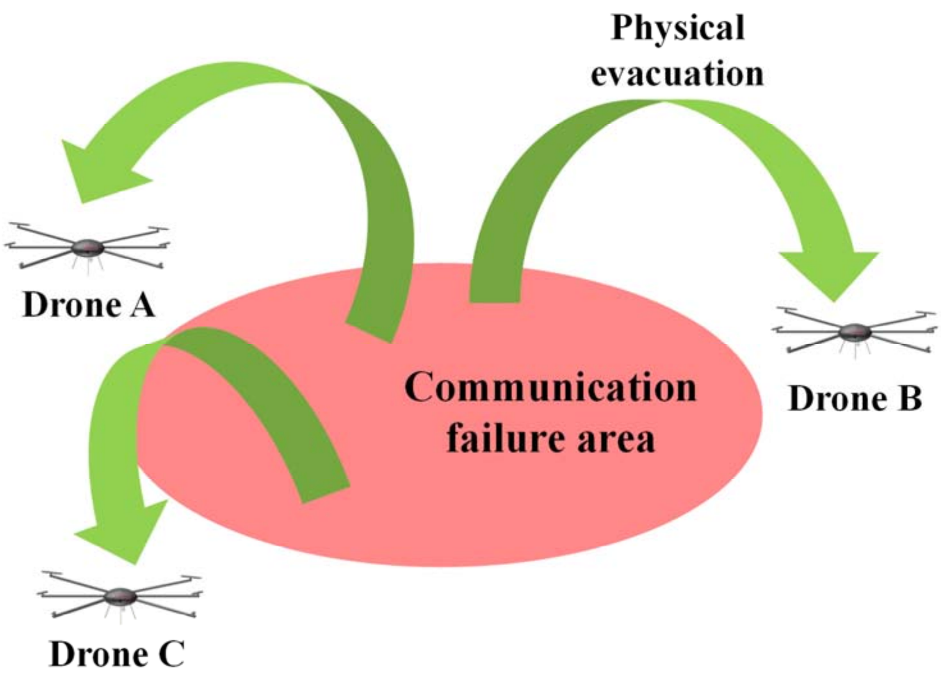


Figure 3.1. Concept of spatial retreat.

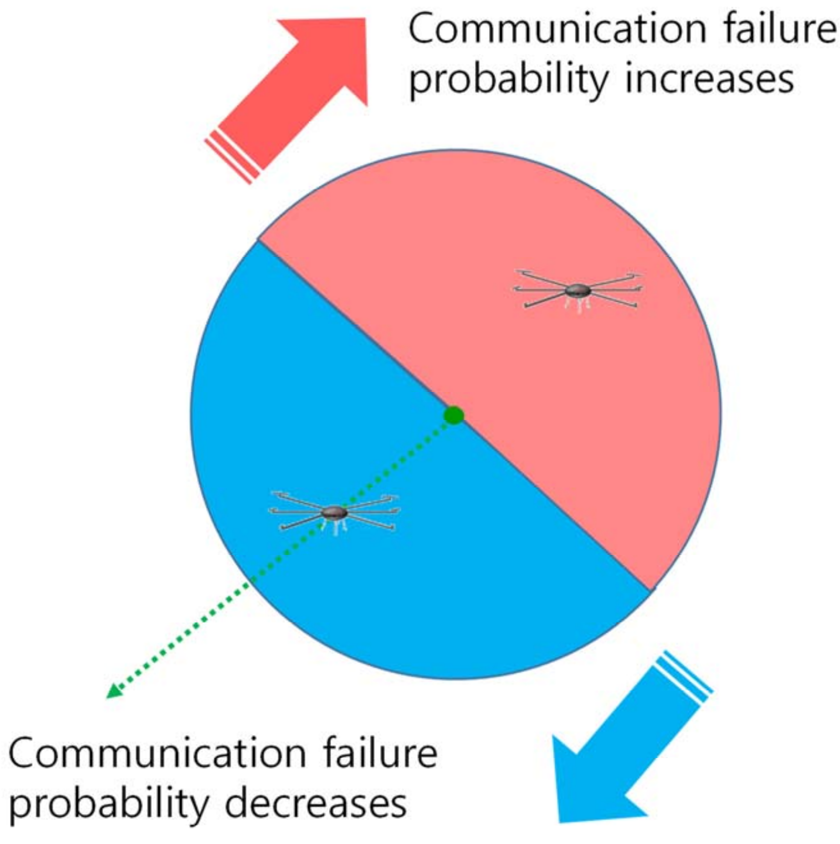


Figure 3.2. Idea of cooperative spatial retreat.

3.2. Cooperative spatial retreat algorithm

```
procedure COOPERATIVE SPATIAL RETREAT
    if DETECT_FAILURE = true then if
        DRONE_MOVING = true then
            move_toward_mission_area()
        else
            turn_on_telemetry()
            for each_drone(i) < number_of_drone do
                get_other_drone_location()
            end for
            set_midpoint() evac
            uate() reconstruct
            phase()
        end if
    else
        normal_phase()
    end if
end procedure
```

Algorithm 1. Cooperative spatial retreat.

The proposed cooperative spatial retreat (CSR), detailed in Algorithm 1, involves a drone that executes an algorithm that utilizes a target drone and its neighboring drones (cooperative drones) to send locational information to the target drone. First, at the DETECT_FAILURE sequence, the target drone needs to detect whether or not it is in the communication failure area by considering information such as the received signal strength indicator (RSSI), packet delivery ratio, carrier sense time, etc [19].

Importantly, when drones are moving to mission areas, evacuation movement might not be required. However, doing so makes it probable that drones will be passing communication failure areas. Here, drones wait before arriving at their destinations by following the DRONE_MOVING sequence. However, if drones are still suffering from communication failure upon arrival, they continue to loop through the CSR algorithm.

In this scheme, each drone that stays in the communication failure area acts as a target drone. The target drone communicates with neighbor drones in the communication failure area by using the assistance communication module of telemetry. This action is triggered by a "turn_on_telemetry" sequence. At this point, target drones collect locational information from other drones in the communication failure area. This action is executed at the "get_other_drone_location" sequence. Consequently, the target drone can calculate the center of gravity between cooperative drones and itself using the "set_midpoint()" sequence. With this information, the target drone can run an evacuate sequence in the exact opposite direction from the center, as shown in Fig. 3.3. In addition, the drone fleet also needs to run a reconstruction phase to reorganize its positional data after running the CSR algorithm for optimal communication.

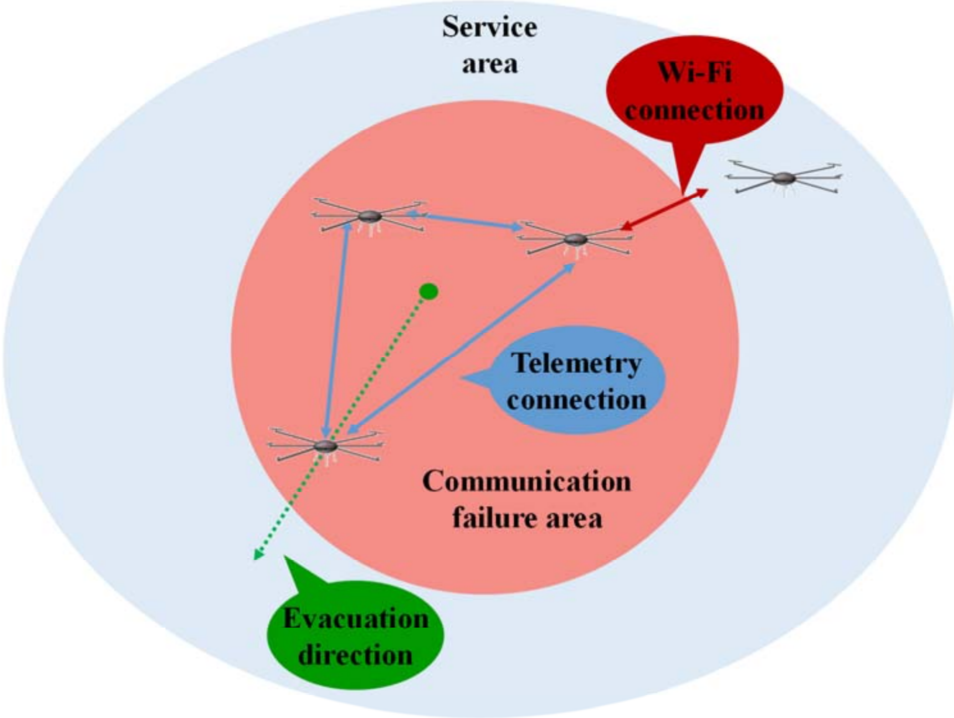


Figure 3.3. Mechanism of cooperative spatial retreat.

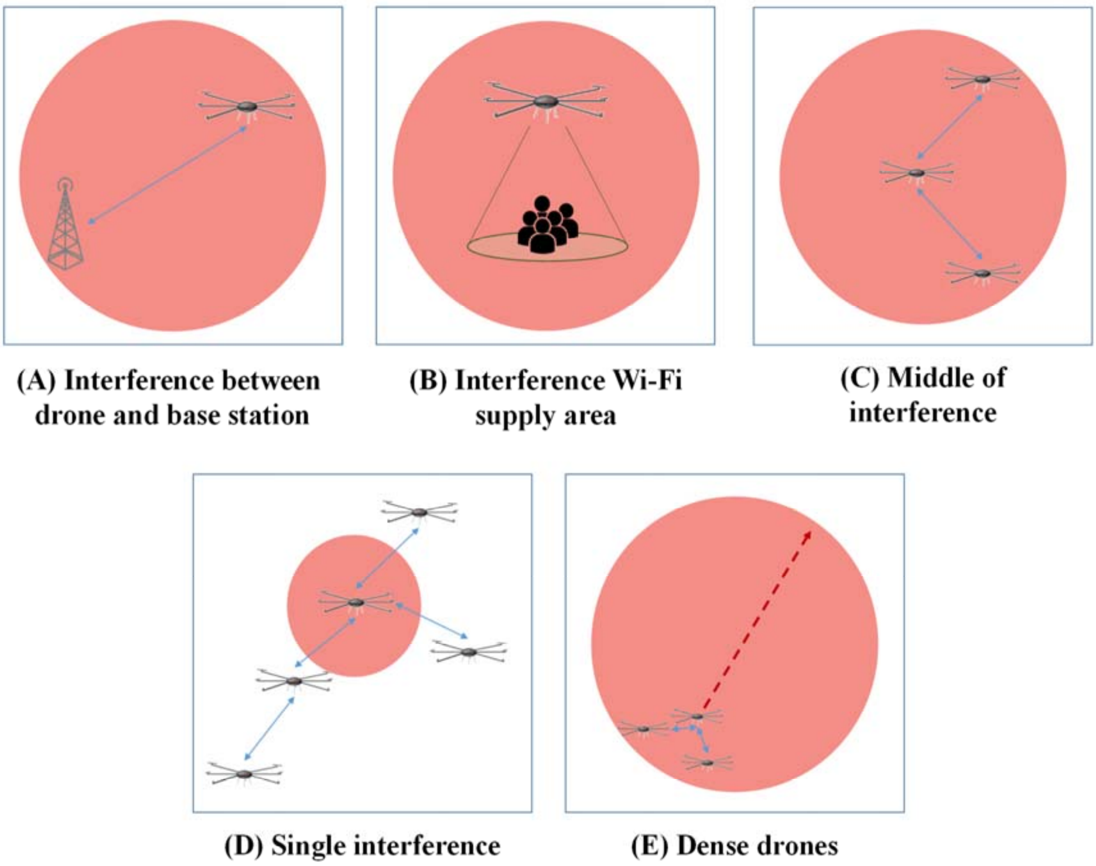


Figure 3.4. Limitations of cooperative spatial retreat.

3.3. CSR failure modes

There are some situations when the proposed CSR algorithm may not properly work, as shown in Fig. 3.4. For example, Situation (A) depicts interference occurring at the base station. Even though net-drones comprise ad-hoc networks, they still need to connect with a base station to provide Internet service for users. Moreover, Situation (B) depicts Internet service users suffering from interference. In this case, users find it harder to move their locations than drones. Hence, the CSR algorithm may be hard to execute.

Situation (C) shows a target drone in the middle of an interference area, at which point the CSR becomes a random escape instruction sequence. In this case, the CSR algorithm provides the same moving distance as a random evacuation even; however, doing so consumes more computational costs. Conversely, Situation (D) shows a single drone located in the communication failure area. Here, the target drone cannot get any reference information from the surrounding drones. Finally, Situation (E) shows drones that are densely located on the boundary of the interference area. In this case, the calculated middle point of interference is quite far from the actual midpoint of interference. Accordingly, the calculated result would be a worst-case scenario. Naturally, the performance of the CSR technique may not significantly outperform random escape.

IV. SIMULATION RESULTS

Table 4.1 Parameters used in the simulation study.

Parameter	Value
Simulation tool	MATLAB (R0213a 8.1.0.604)
Simulation dimension	Three-dimensional plane
Shape of the communication failure area	Circle
Radius of the communication failure area	100 (m)
Maximum evacuation distance	200 (m)
Number of comparison groups	4

In this section, we compare the performance of the CSR with conventional spatial retreat. In particular, we compare the moving distance for evacuation from the communication failure area. The parametric values used in our simulation study are summarized in Table 4.1.

4.1. Comparison groups

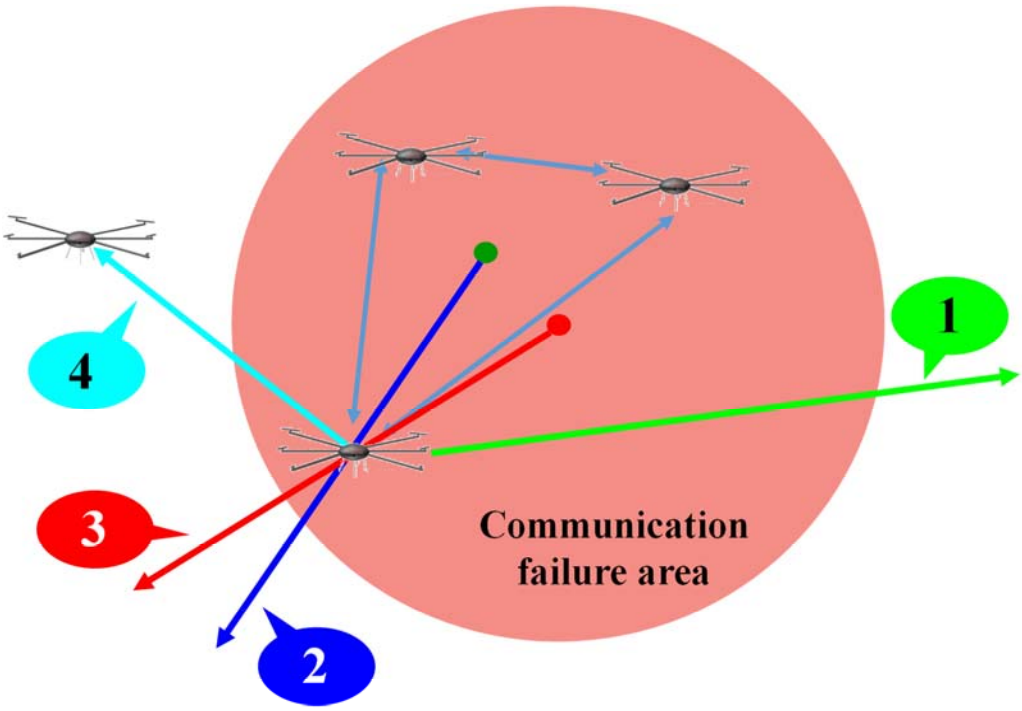


Figure 4.1. Simulation comparison groups.

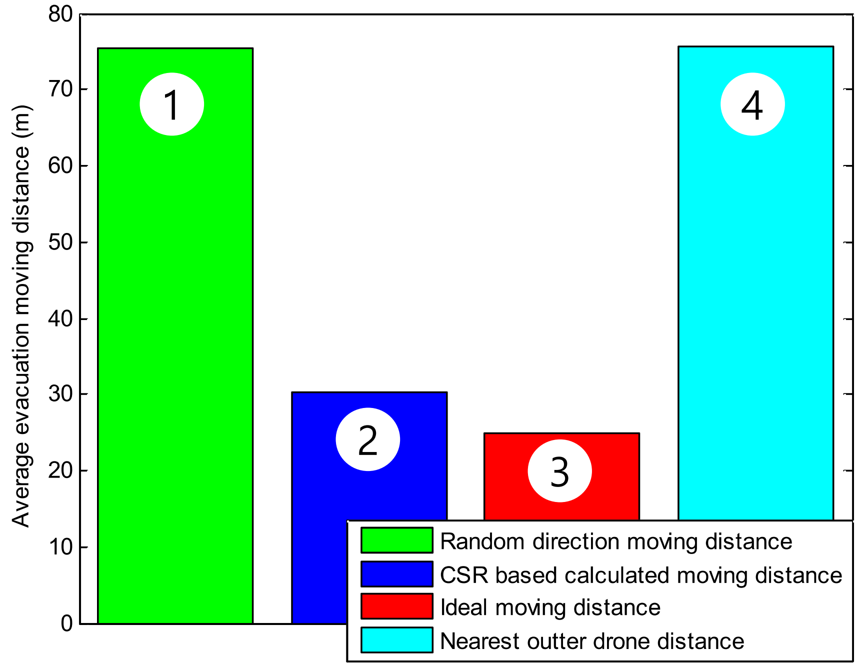
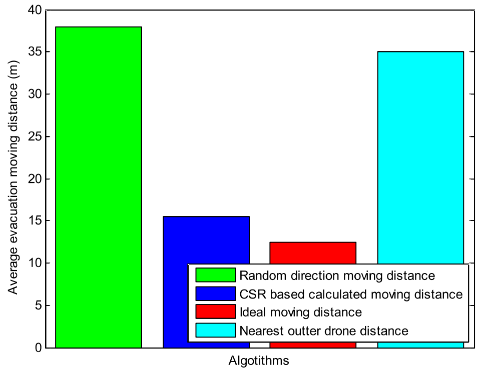


Figure 4.2. Evacuation distance per comparison groups.

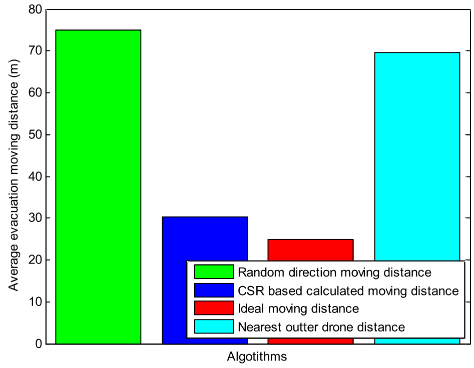
In our simulation study, we used 4 comparison groups. Fig. 4.1 illustrates the main features of each comparison group, while Fig 4.2 shows how far the target drone moved to evacuate the communication failure area. The first comparison group utilized a conventional spatial retreat scheme in which it randomly evacuated the communication failure area. Hence, it had the worst efficiency. The second comparison group utilized our proposed cooperative spatial retreat (CSR) technique; whereas, the third comparison group was our ideal case, meaning that the group exhibited perfect movement with full information. Finally, the last comparison group utilized a technique in which the target drone would evacuate to the nearest drone outside of the communication failure area. We expected that this method would perform quite well, but this did not turn out to be the case.

As given in Fig. 4.2, the average moving distance of the CSR was less than half of that of the conventional scheme. Furthermore, the performance of the CSR was comparable to that of the optimal scheme with full knowledge of the communication failure area. In the following section, we will describe in detail the results of each comparison groups.

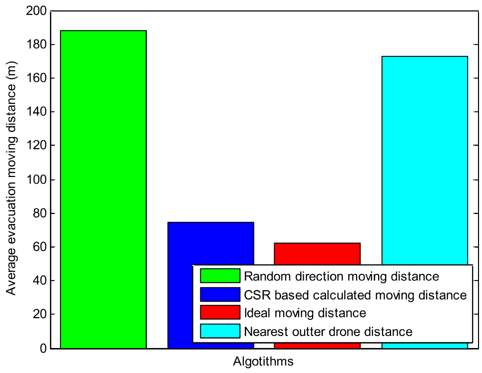
4.2. Influence of communication failure area



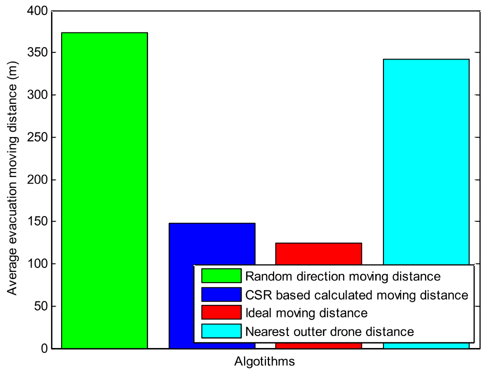
(a)



(b)



(c)



(d)

Figure 4.3. Evacuation distance of different radius of communication failure area, (a) 50m. (b) 100m. (c) 250m. (d) 500m.

Firstly, we execute simulation about effect of communication failure area size. Each simulation result use same 3 inner drones and 3 outer drones. Also, simulation executed 10000 time per each graph. Other parameters are the same as in Table 4.1. There are four simulation result about influence of communication failure area size. Evacuation distance is increasing as much communication failure area size increasing. However, the ratio of each comparison groups are the same. Hence, we conclude that communication failure size does not affect evacuation distance efficiency.

4.3. Evacuate to nearest outer drone

The way we think ahead of the cooperative spatial retreat method is simply to avoid the nearest drone at the outside of communication failure area as shown in Fig 4.4. Our idea was that if drones existed at the outside of communication failure area, that place must not communication failure area. Hence, drones easily evacuate from communication failure area. However, the efficiency of this idea was not as good as we expected. Evacuation distance efficiency is increasing as much outer drones increasing but, even though hundreds outer drones are used, evacuation distance is not much different with the random direction evacuation distance as shown in Fig 4.5. That simulation executed 10,000 times per graph and used 2 inner drones.

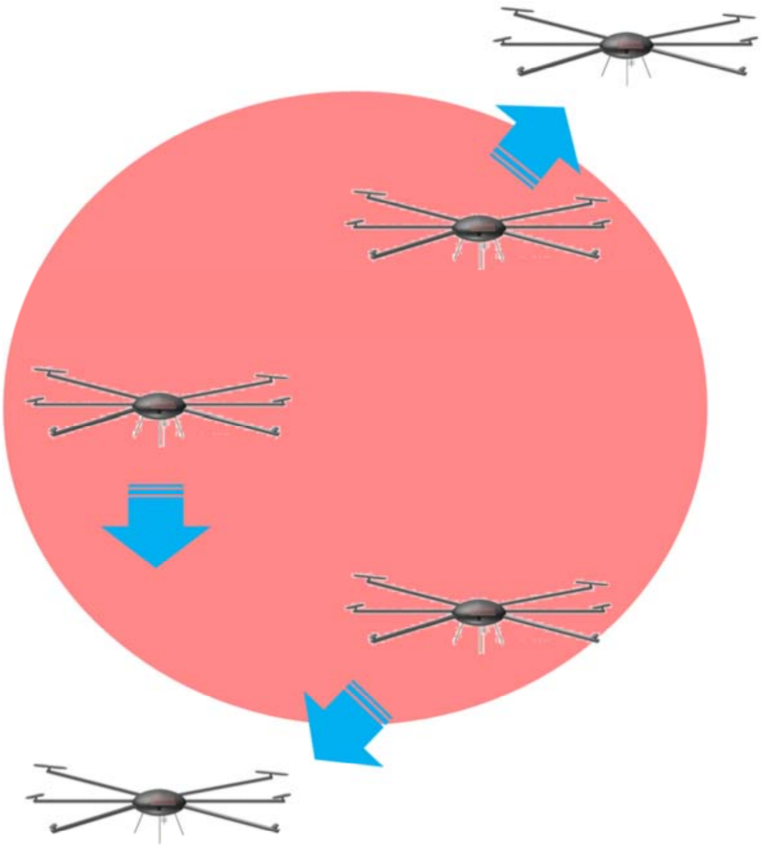


Figure 4.4. Idea of evacuate to nearest drones.

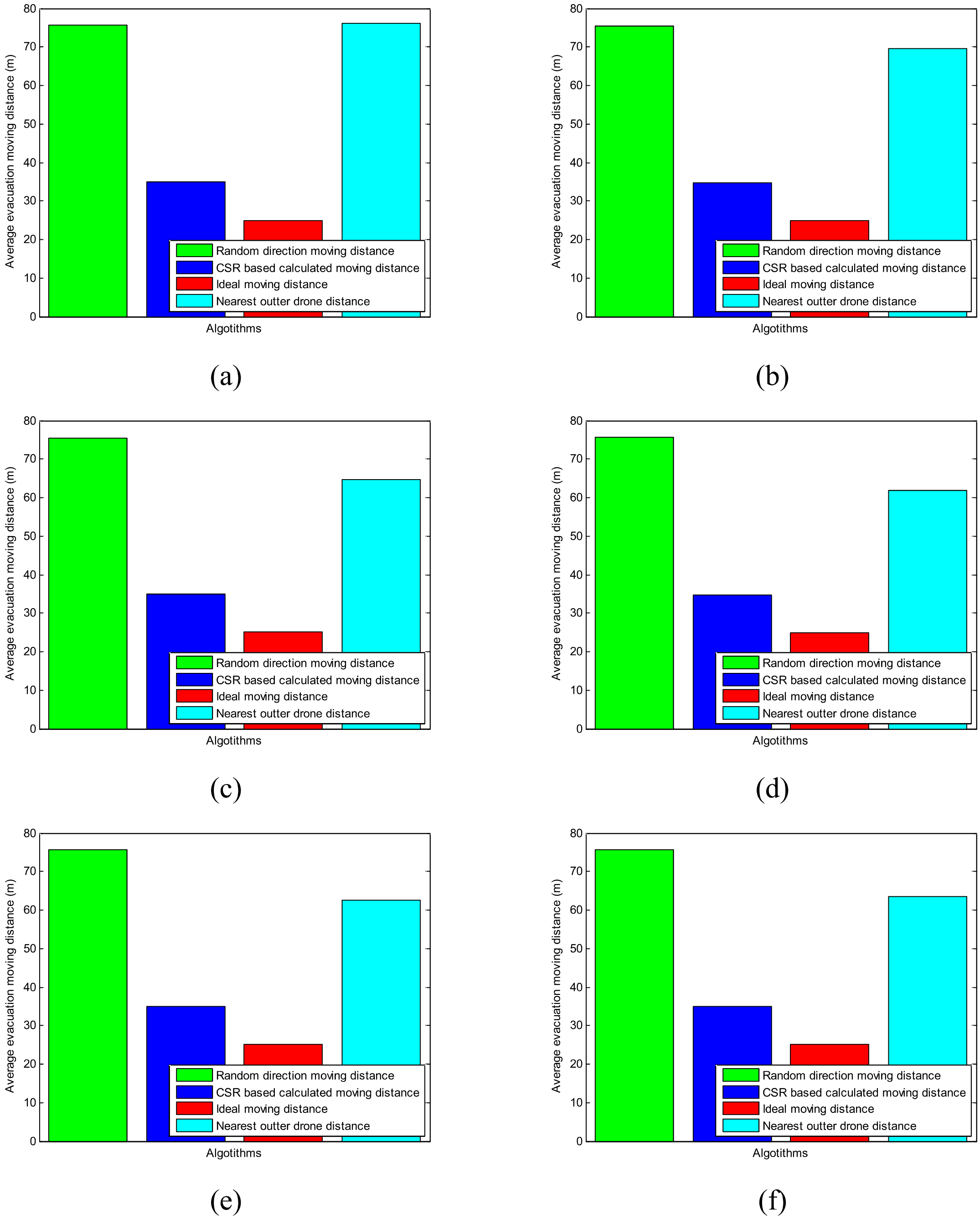


Figure 4.5. Evacuation distance of different outer drones,
(a) 2 outer drones. (b) 3 outer drones. (c) 5 outer drones.
(d) 8 outer drones. (e) 50 outer drones. (f) 100 outer drones.

4.4. Cooperative spatial retreat

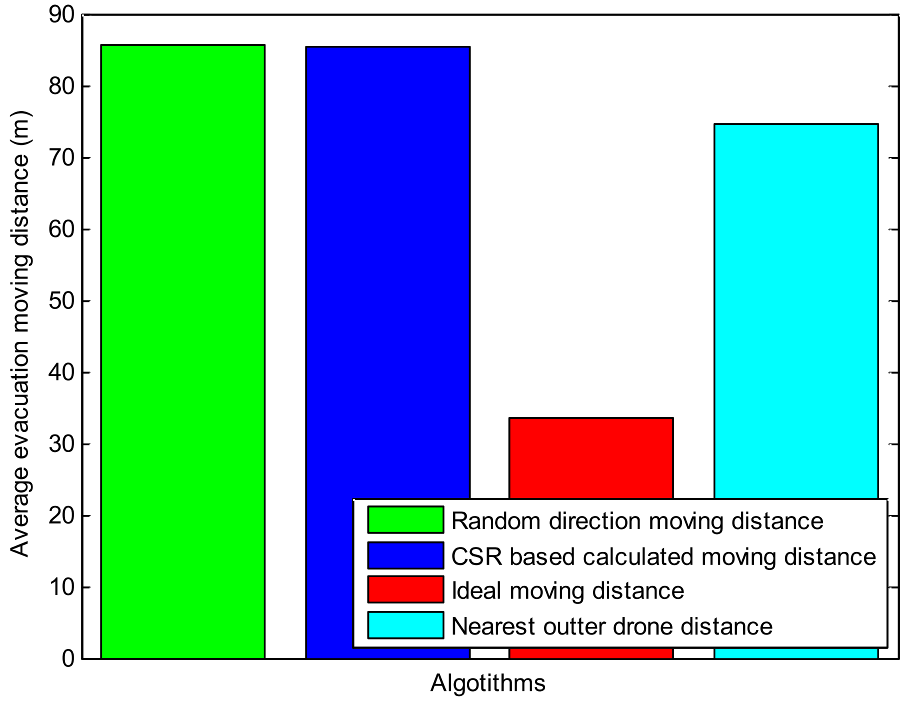


Figure 4.6. Evacuation distance of single drone case.

As mentioned in the previous section, a single drone in the communication failure area exhibited the same efficiency in random direction evacuation as our CSR as shown in Fig. 4.6. Except these kind case here, the evacuation distance efficiency rapidly increased as the number of cooperative drones increased, as shown in Fig. 4.7. In the case that there were more hundreds of cooperative drones, the efficiency of the cooperative spatial retreat was similar to that of the ideal moving distance.

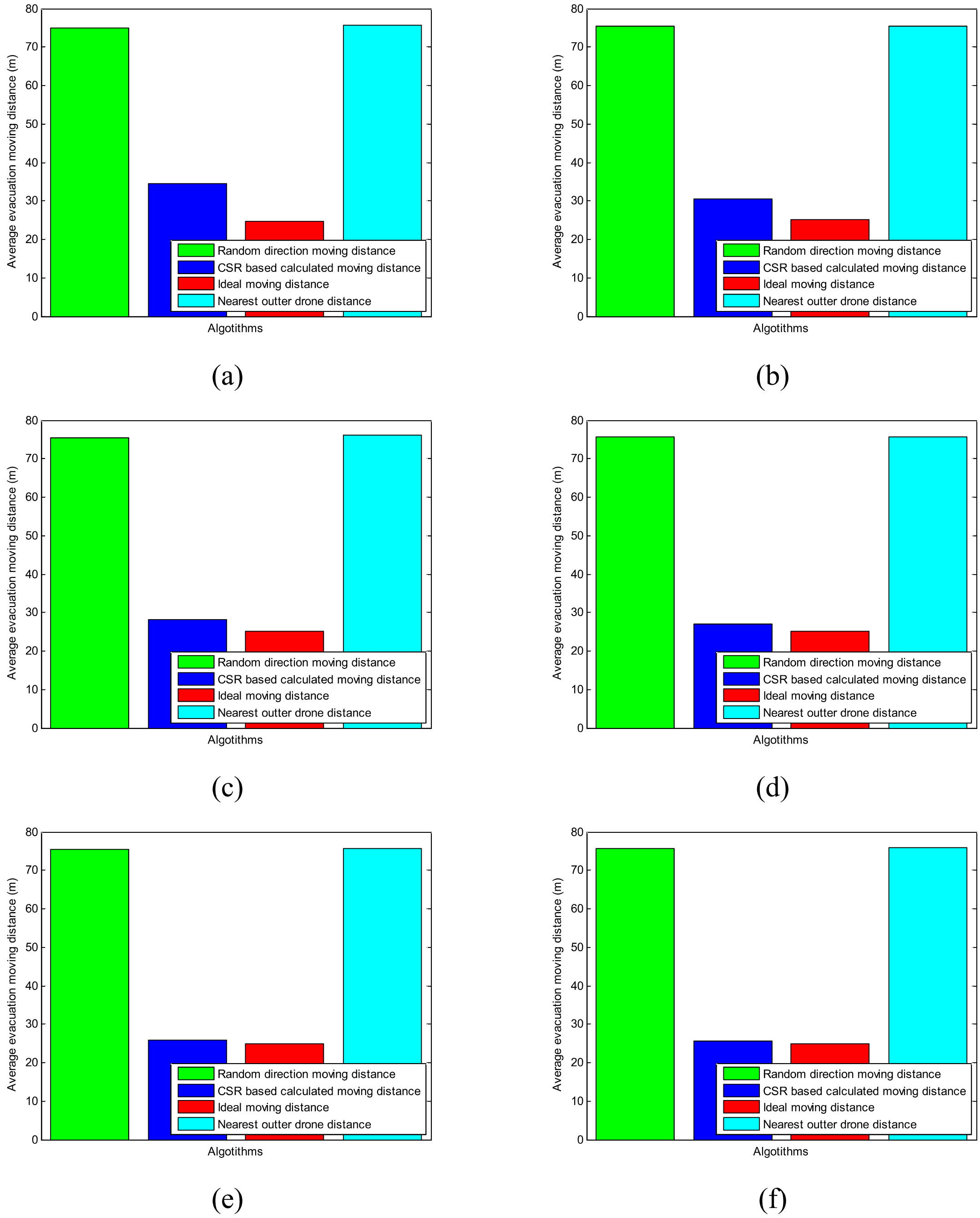


Figure 4.7. Evacuation distance of different inner drones,
(a) 2 inner drones. (b) 3 inner drones. (c) 5 inner drones.
(d) 8 inner drones. (e) 50 inner drones. (f) 100 inner drones.

The moving distance efficiency was mainly effected by the dense drone problem, as mentioned in Section 3.3. Fig. 4.7 shows the differences between each comparison group in every simulation test case. Here, there were two outer drones used. Normally, the moving distance using the CSR method was shorter than that of the random direction tactic. However, sometimes the CSR moving distance was comparatively high. This was a result of the dense drone problem, marked as a red circle in Fig. 4.8.

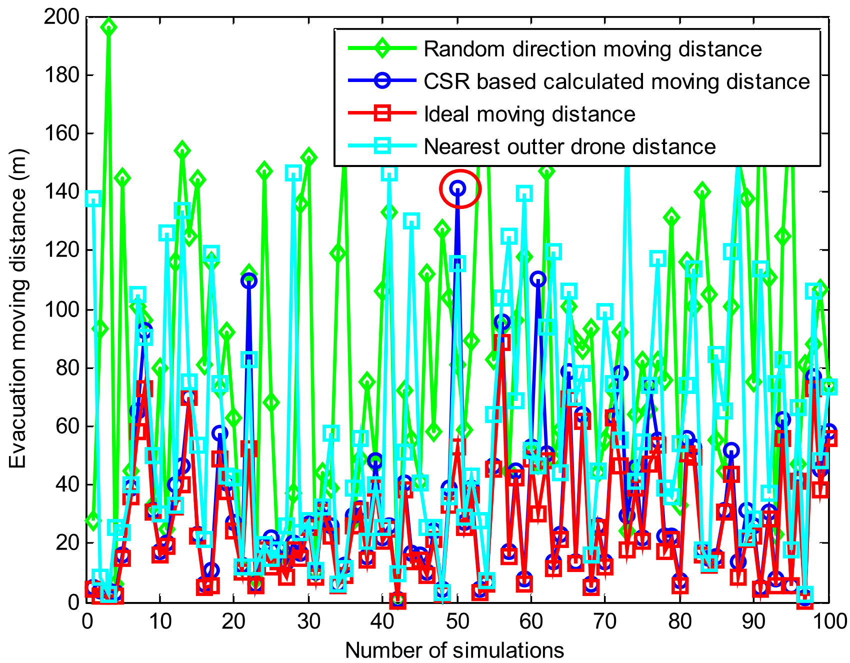


Figure 4.8. Test case of dense problem.

However, since the dense problem is relatively small compared to the whole sample, using the CSR algorithm would be useful for drone to avoid effectively in the communication failure area.

V. CONCLUSIONS

In this paper, we propose an efficient spatial retreat scheme, the cooperative spatial retreat (CSR) algorithm, to enhance the reliability of net-drones in providing network service. By using the proposed scheme, net-drones were able to get out of the communication failure area and provide reliable network service in simulations. Unlike the conventional spatial retreat mechanisms, which assume a two-dimensional area, we consider that a drone can evacuate utilizing three dimensions.

Additionally, drones using the conventional spatial retreat technique randomly evacuated the communication failure area; whereas, drones following the CSR scheme evacuated in highly efficient directions. Accordingly, the energy of each drone was mostly consumed in floating and moving. Hence, our proposed scheme is helpful in extending the battery lifetime of drones. In addition, our continuous axis update function increases their overall efficiency, given that only a single drone can evacuate to propel the direction using this method. We confirmed the efficiency of our proposed CSR method using simulation studies.

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요 약 문

통신장애지역에서 넷드론 네트워크의 신뢰성을 향상하기 위한 협동공간회피기법

최근 드론은 농업, 정찰, 배송, 방송, 레저 등 분야를 막론하고 그 영역을 넓혀나가고 있다. 하지만 드론이 더 대중화 되기위해서는 극복해야만 하는 기술적인 문제들이 있다. 그 중의 하나는 통신에서의 신뢰성이다. 현재 대부분의 드론들은 무선으로 조종이 되며 이는 지속적인 통신없이 미션을 완수하기 힘듬을 의미한다.

드론의 통신이 간섭, 시야각, 재밍 등으로 인하여 원활하지 않을 때 가능한 방법 중 한가지가 공간회피기법이다. 이는 드론이 통신장애지역에 들어섰을 때 그 공간으로부터 물리적으로 회피하는 기법이다. 기존의 공간회피기법은 오직 무작위 방향으로 회피를 하였기 때문의 이동거리의 효율성과 정확성이 적합하지 않았다.

본 논문에서 우리는 네트워크 신뢰성을 향상시키기 위해서 더 효율적인 회피 기법을 제시하였다. 협동공간회피가 그 명칭이며 우리는 이 기법에서 텔레메트리 통신 모듈을 사용함으로써 상당한 성능의 향상을 시뮬레이션을 통하여 검증 하였다.

핵심어: Aerial networks, Drones, UAV, UAS, Spatial retreat, Topologic management