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Emergency communication service solution based on UAV swarm

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Abstract. It has a broad application prospect to provide communication services with UAVs. In this paper, the authors propose an emergency communication service scheme based on UAV swarm, which can provide users with stable network connection to communication services when they are far from the base station. In our design, multiple UAVs will be placed in the middle of the base station and the target area to form a multi-antenna array. Beamforming technology is applied to increase the signal strength through the UAV and transmit the signal from the base station to the target area. Above the target area, we will deploy multiple UAVs using OFDM technology to provide signal relay services for users below. Through simulation and calculation on MATLAB and python, we verify the feasibility and applicability of this scheme.

Keywords: UAV swarm, multiple antenna, beamforming, OFDM, communication service.

1. Introduction

1.1. Research background

Natural disasters often lead to the damage of the base station, which leads to the interruption of communication services such as mobile phones and network connections. How to restore communication services in this case is a problem with strong practical value. At present, there are many UAV-based emergency communication service solutions. In 2021, in Zhengzhou, China, government departments used large UAV to provide stable 2G network connections for users who lost communication services due to heavy rain. However, in the current solution, people often use large UAV, which makes the deployment of the UAV more difficult. At the same time, the data rate provided by the current solution can only meet the needs of phone calls and text messages. How to make the UAV-based emergency communication service solution easier to deploy and provide greater data rate has become our concern.

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1.2. Related work

Y. Zeng, Q. Wu and R. Zhang [1] presented the overall vision of applying UAVs to communication systems, especially 5G communication systems On the application of UAV, K. Mase and H. Okada [2] introduced the application of UAV in severe disasters. They introduced a temporary messaging system that can be deployed rapidly across the affected area. On how to deploy UAVs, E. Kalantari, H. Yanikomeroglu and A. Yongacoglu [3] studied the number of UAV base stations and their 3D layout in wireless cellular networks. In terms of communication means and technology, K. Mase [4] studied how to transmit the signal to the affected area. Cheong Yui Wong, R. S. Cheng, K. B. Lataief and R. D. Murch [5] introduced the problem of multi-user orthogonal frequency division multiplexing (OFDM) with adaptive multi-user subcarrier allocation and adaptive modulation. K. Ali, H. X. Nguyen, Q. Vien, P. Shah and M. Raza [6] study on the Stability and Throughput of UAV as Signal Base Station.

2. Requirements setting and communication environment model selection

In order to better construct, analyze and evaluate our solution, we assume the application scenarios of this solution, set the environment, distance, number of target users and data rate, and select the communication models applied to the horizontal and vertical directions according to these settings.

2.1. Application scenario setting

We assume that the type of area that needs communication services is suburban, the area is $500m * 500m$ square area, and the horizontal distance between the regional center and the nearest base station is 2000m, only one base station can provide communication services for the target area. In the target area, there are 200 users randomly distributed, our solution needs to provide 1Mbps stable network speed for each user, and the bit error rate(BER) should be lower than 10^{-3}. The relationship between base station, target area and users are shown in Fig. 1.

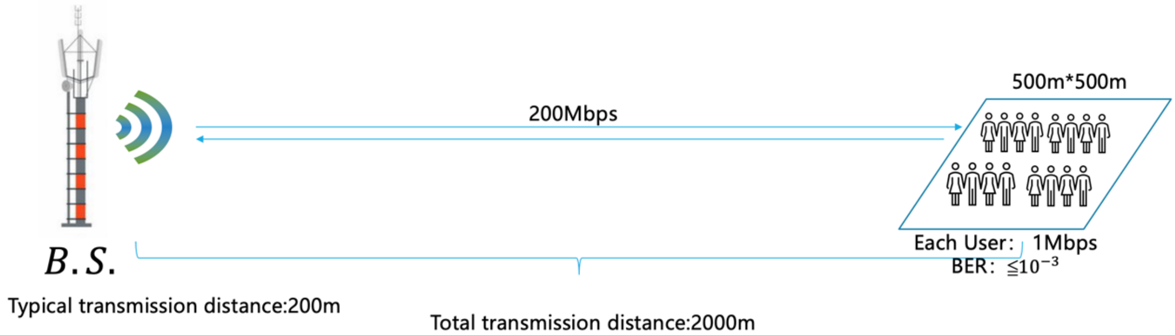

Figure 1. Relationship between base station, target area and users.

We assume that the transmission power of the base station is 0.1 W, and the transmission power of each UAV is 0.01 W or 0.1 W. To reduce the cost of the system, our goal is to use narrower bandwidth, fewer UAVs and lower transmission power.

2.2. Communication environment model selection

In the process of signal transmission, different environments and distances will lead to different path loss(L_P), thereby leading to changes in the receiving power. In the process of establishing the system, we choose different models to calculate the path loss according to the different environments in order to better quantify the change of received power. When the L_P and transmitting power are determined, we can calculate the receiving power according to the following formula:

When the UAV is placed on a line to provide relay service,

$$Received\ Power(Pr) = \frac{P_t G_r G_t}{L_P L_r} \tag{1}$$

When UAVs are used as multiple-antenna and receive signals,

$$Received\ Power(Pr) = \frac{NP_tG_rG_t}{L_PL_r} \tag{2}$$

When UAVs are used as multiple-antenna and transmit signals,

$$Received\ Power(Pr) = \frac{N^2P_tG_rG_t}{L_PL_r} \tag{3}$$

In the above formula, P_t is the transmitting power, G_r and G_t are the gain of transmitting antenna and receiving antenna, L_P is the path loss, and L_r is the implementation loss, which is a constant. N is the number of UAVs used as multi-antenna, and changes in transmission power and antenna gain are brought according to the difference between transmitting and receiving.

Next, we will select different models to calculate L_P according to different stages of signal transmission.

2.2.1. Free space model. This model is mainly applied to the communication between UAVs in horizontal and vertical directions and the communication between UAVs and base stations. Because there is a certain distance between the UAV and the ground, in this model, we approximately believe that the signal transmission is not blocked by obstacles, but also not reflected by the ground. In free space model, L_P is given by Friis's formula [7]:

$$Path\ Loss(L_P) = \left(\frac{4\pi d}{\lambda_c}\right)^2 = \left(\frac{4\pi f_c d}{c}\right)^2 \tag{4}$$

f_c is the carrier frequency and d is the transmission distance. In dB, L_P can be written as:

$$L_{P(dB)} = -20log10\left(\frac{c}{4\pi}\right) + 20log10(f_c) + 20log10(d) \tag{5}$$

2.2.2. Two ray ground reflection model. This model is applied to the communication links between UAVs and users, since the users are on the ground and there will be an additional ground reflected wave. In this model, the shadowing fading factor is not considered. Therefore, for a unique distance, the P_r is a deterministic value. In two ray ground reflection model, L_P is calculated by following formula [8]:

$$\tau(\theta) = \frac{sin\theta - X}{sin\theta + X} \tag{6}$$

θ is the reflection angle of the ground reflected wave and X can be decomposed into X_h and X_v, which can be calculated by following formula:

$$X_h = \sqrt{\varepsilon_g - cos^2\theta} \tag{7}$$

$$X_v = \frac{X_h}{\varepsilon_g} \tag{8}$$

Where ε_g is the relative permittivity of the ground.

$$\Delta_\varphi = \frac{2\pi(d_{ref} - d_{los})}{\lambda} \tag{9}$$

Where λ is the wavelength of the signal and d_{ref}, d_{los} can be calculated by Pythagorean Theorem and the law of reflection:

$$d_{ref} = \sqrt{(h_{UAV} + h_{user})^2 + d^2} \tag{10}$$

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$$d_{los} = \sqrt{(h_{UAV} - h_{user})^2 + d^2} \tag{11}$$

Where h_{UAV} is the altitude of UAV, h_{user} is the height of the user and d is the horizontal distance between UAV and the user.

Finally, the L_P can be calculated by this formula:

$$L_P = 10\log\left(\left|\frac{\lambda}{4\pi}\left(\frac{\sqrt{G_{los}}}{d_{los}} + \frac{\tau(\theta)\sqrt{G_{ref}}e^{-j\Delta_\varphi}}{d_{ref}}\right)\right|^2\right)(d) \tag{12}$$

Where G_{los} and G_{ref} are gains of antenna along the LoS path and the reflection path.

3. System design

In this section, we will show the overall design of the solution, and the scheme is divided into horizontal and vertical two parts to show the specific technical details.

3.1. Presentation of overall design

We have 25 UAVs in total to provide communication services for 200 users. 8 of the 25 UAVs are placed at the midpoint of the target area and the base station, forming a multiple-antenna array to enhance signal strength. A 0.1 watt UAV (A0) is placed directly above the target area. The other 16 UAVs are placed below A0, connecting users and relay UAV(A0). The position relationship between each UAV and users and base stations is shown in Fig. 2.

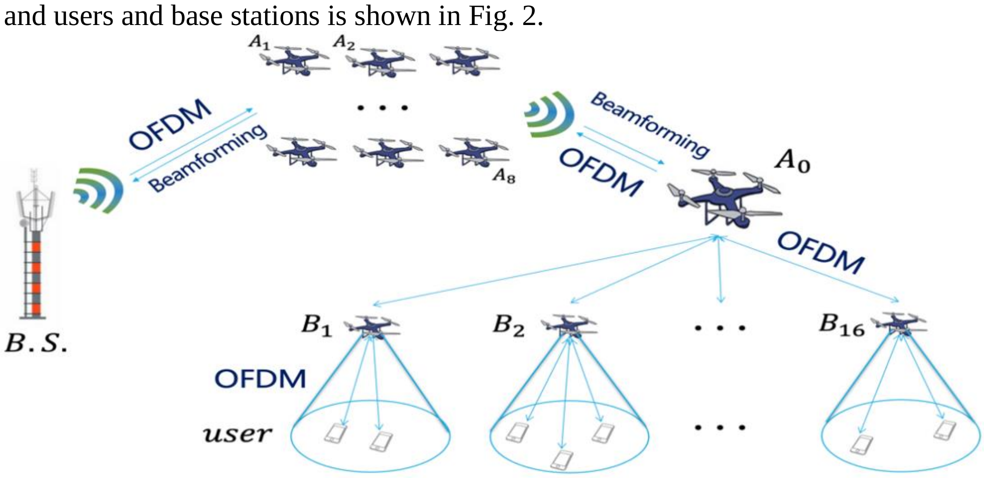

Figure 2. Overall design sketch map.

3.2. Technical details in horizontal link

In the horizontal direction, the information of 200 users is transmitted as a whole without considering the distribution of signals. Therefore, the data rate required in the horizontal direction is 200Mbps. To meet the requirements and use as narrow bandwidth and as few UAVs as possible, we used OFDM and beamforming. Among them, OFDM can effectively reduce the bandwidth by Orthogonalizing subcarriers, beamforming can improve the signal directivity and therefore improve the transmission distance. The directivity of different number of multiple-antenna is shown in Fig. 3.

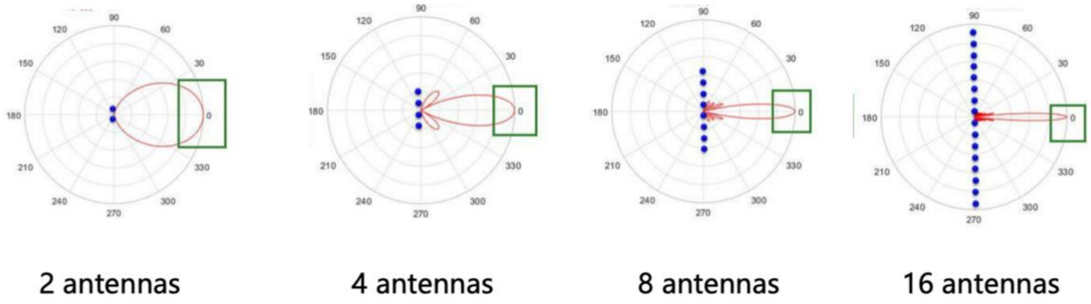

Figure 3. Directivity of different number of multiple-antenna.

We selected the carrier frequency of 3GHz, and set 64 subcarriers, gave each subcarrier a width of 1MHz. When the signal is transmitted by 8 UAVs used as multiple-antennas, beamforming technology is applied, and the transmission power and the gain of transmitting antenna(G_t) will be increased. When the signal is transmitted by the relay UAV(A0) or the base station, we use OFDM to transmit the signal and obtain an increase in the gain of receiving antenna(G_r). The main technical parameters are shown in Table 1.

Table 1. Main parameters in horizontal link.

Indicator	Value/Result
Carrier Frequency	3GHz
Number of Subcarriers	64
Bandwidth of Each Subcarrier	1MHz
Total Bandwidth	32.5MHz
Number of UAV as Multiple-Antenna	8
Modulation Mode	16qam
Altitudes of UAVs	984.5m

3.3. Technical details in vertical link

In the vertical direction, we assume that the link between A0 and B is Free Space Propagation Model. This is because the receiver and transmitter are completely unblocked, while the link between B to user will be the Two-Ray-Ground-Reflection Model since the users are on the ground, which reflects signals sent to users and affects the entire transmission process of the signal. Moreover, we consider users to be randomly distributed. We also used OFDM in vertical part to use as narrow bandwidth as possible and the reason has been explained in the previous section.

We set the carrier frequency at 3GHz and 200 subcarriers, gave each subcarrier a width of 1MHz. Signals will be transmitted by 16 UAVs(B), which are respectively responsible for a certain range of users. We also determined that the altitudes of UAVs(B) are 176.8m and altitude of UAV(A0) is 984.5m. The modulation mode will be QPSK, which helps decrease the total bandwidth to 100MHz. The main technical parameters are shown in Table 2.

Table 2. Main parameters in vertical link.

Indicator	Value/Result
Carrier Frequency	3GHz
Number of Subcarriers	200
Bandwidth of Each Subcarrier	1MHz
Total Bandwidth	100.5MHz
Number of UAV(B)	16
Modulation Mode	QPSK
Altitudes of UAVs(B)	176.8m
Altitude of UAVs(A0)	984.5m

4. Analysis & simulation

In this section, we use MATLAB and python to analyze our system to verify that the design can meet our design goals. At the same time, we compared the performance of the system under different ways of placing UAVs and different modulation modes to show the performance of the design in achieving the goal of using narrower bandwidth and fewer UAVs.

4.1. Analysis of horizontal design

In the horizontal direction, we mainly need to analyze whether the data rate requirements and BER requirements of each user can be met. We mainly consider four signal modulation modes that can be used in OFDM technology. Different modulation modes have different bit per transmit symbol rate(b_k), thus, the required SNR is different. The formulas that are used to calculate different SNR for different modulation mode are as follows:

When modulation mode is BPSK, the required SNR(snr) can be calculated as,

$$snr_{(dB)} = 10log10\left(erfc^{-1}(2 \times BER)\right)^2 \tag{13}$$

When modulation mode is QPSK, the required SNR(snr) can be calculated as,

$$snr_{(dB)} = 10log10\left[\left(erfc^{-1}(2 \times BER)\right)^2 \times 2\right] \tag{14}$$

When modulation mode is 16qam, the required SNR(snr) can be calculated as,

$$snr_{(dB)} = 10log10\left[\left(erfc^{-1}(2 \times BER \times 4/3)\right)^2 \times 5/2\right] \tag{15}$$

When modulation mode is 64qam, the required SNR(snr) can be calculated as,

$$snr_{(dB)} = 10log10\left[\left(erfc^{-1}(3 \times BER \times 8/7)\right)^2 \times 7\right] \tag{16}$$

According to the formula (13) to (16), we can get the analysis results of different modulation modes, which is shown in Table 3.

Table 3. Analysis results of different modulation modes.

Modulation Mode	bk	Required Bandwidth	Required SNR(snr)
BPSK	1	256MHz	6.7985dB
QPSK	2	128MHZ	9.7998dB
16qam	4	64MHz	16.5430dB
64qam	6	42MHz	22.5490dB

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In order to compare the number of UAVs required under different placement methods, we envisage three ways of placing UAVs, namely, placing the UAV on a line as a relay UAV, using the UAV as multiple-antennas all over the target area and placing the UAV at the midpoint of the base station and the target area. The schematics of these three placements are shown in Fig. 4.

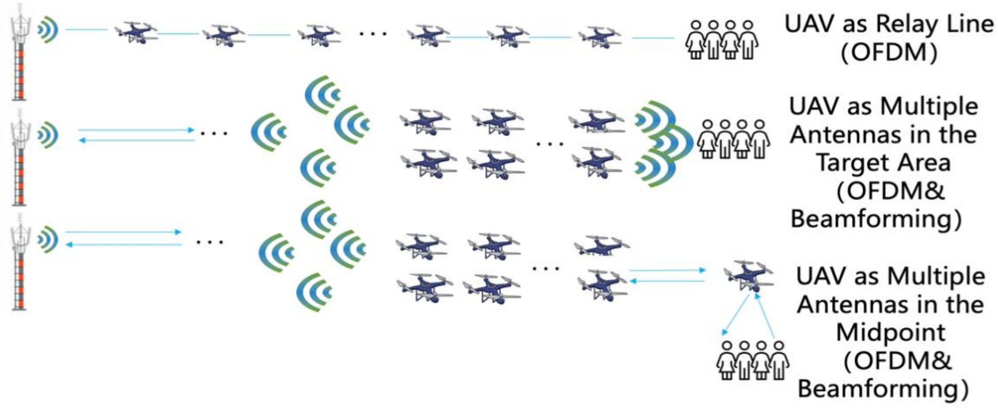

Figure 4. Three ways of placing UAVs.

According to the SNR calculation formula:

$$SNR = \frac{P_t G_r G_t}{k T_0 B_w F L_p L_r} \tag{17}$$

Where k is Boltzmann's constant and T_0 is typical room temperature(290k), together with the analysis results in Table 4, we can obtain the required bandwidth and the number of UAVs under different modulation modes and different UAV placement methods, as shown in Table 4.

Table 4. Required number of UAVs for different modulation mode & placement method.

Modulation Mode	Maximum relay distance	Bandwidth needed	UAV needed for relay line	UAV needed for multiple antennas	UAV needed when been put in the midpoint
BPSK	202.33m	256MHz	10	10	6
QPSK	202.33m	128MHz	10	10	6
16qam	131.65m	64MHz	16	24	9
64qam	90.46m	42MHz	23	49	14

Based on the results in table 4, we believe that our solution (using 16qam as modulation mode and placing UAVs at the midpoint as multiple-antennas) can have both smaller number of UAVs needed and narrower bandwidth requirements. Therefore, we believe that our solution meets the design requirements in the horizontal direction and has certain advantages over other solutions.

4.2. Analysis & simulation of vertical design

In the vertical direction, we also need to use the method mentioned in the previous section, especially formulas (13) to (17), to analyze whether the data rate requirements and BER requirements of each user can be met. However, the difference is that Path Loss is calculated differently, that is, the calculation method proposed in the Two Ray Ground Reflection model section above. To get all the parameters required by the formula(12), the placement of UAVs(B) should be determined first.

We considered the case of different numbers of B separately, such as 1, 2, 4, 8, 9 and 16. For the case of one UAV, we center it at 500m by 500m square which is shown in Fig. 5.

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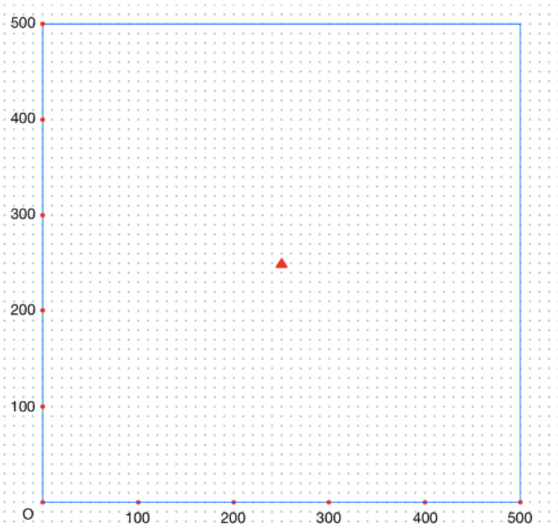

Figure 5. One UAV placement

For the case of more than one UAVs, we considered that the distance between each UAV is the main factor affecting the placement, because the father distance is, the larger scale of users the swarm of UAVs can serve independently.

Therefore, in the case of two UAVs, we need to choose which way we place the UAV as shown in Fig. 6. According to the selection basis mentioned above, the distance between UAVs in placement II is farther, so we choose placement II in Fig. 6.

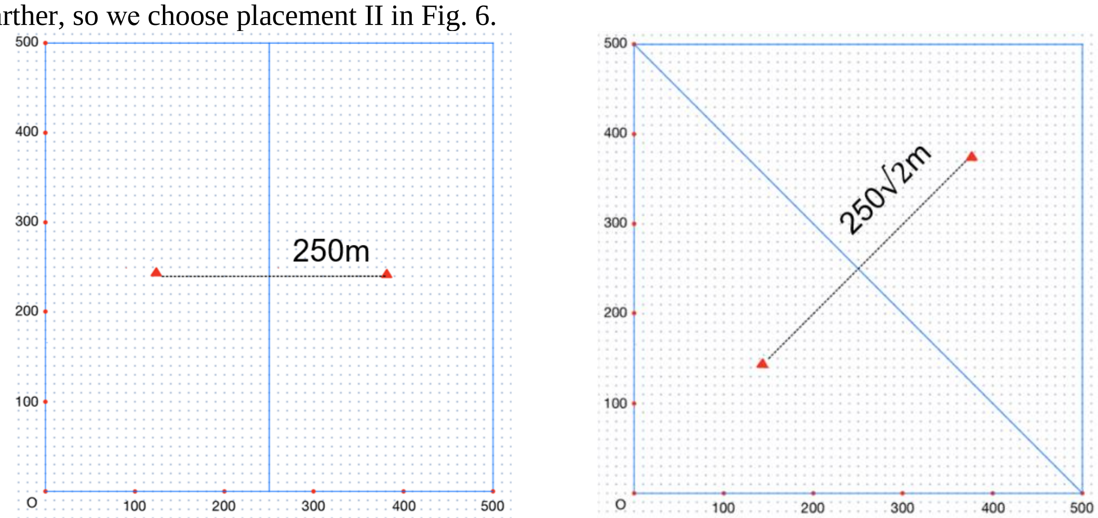

Figure 6. Two UAV placement : I, Two UAV placement : Ⅱ.

In the case of four UAVs , the distance between the UAVs is farther in placement II in Fig. 7 below, which will be the chosen placement.

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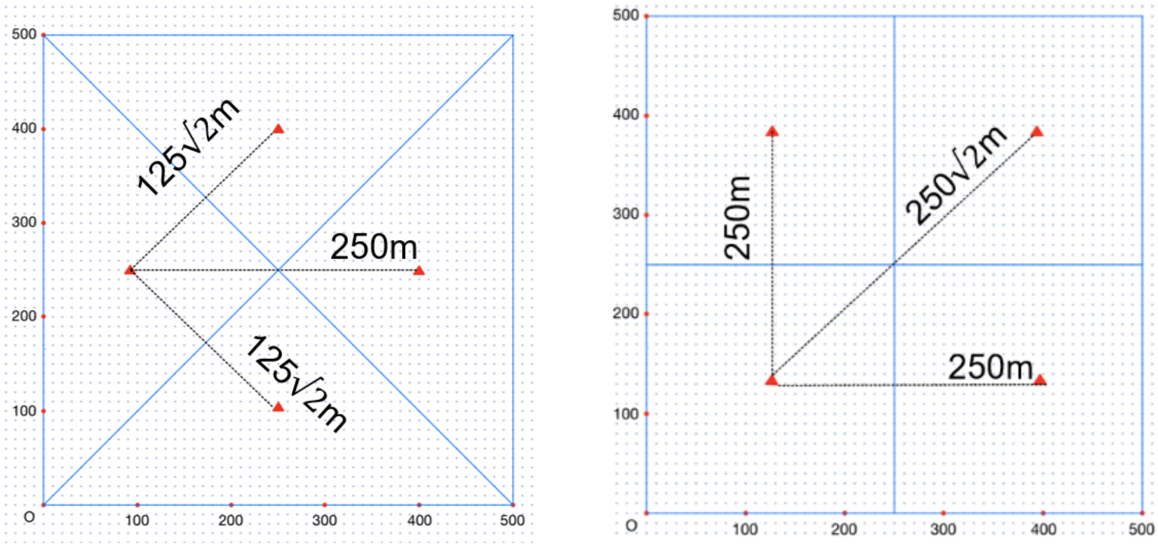

Figure 7. Four UAV placement Ⅰ, Four UAV placement Ⅱ.

Similarly, we chose the placement shown in Fig. 8. as the placement of the case of eight UAVs, the placement shown in Fig. 9. as the placement of the case of nine UAVs, the placement shown in Fig. 10. as the placement of the case of sixteen UAVs.

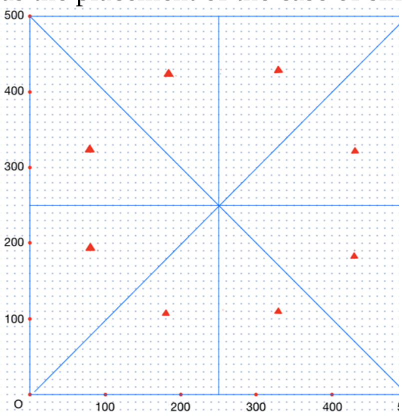

Figure 8. Eight UAV placement.

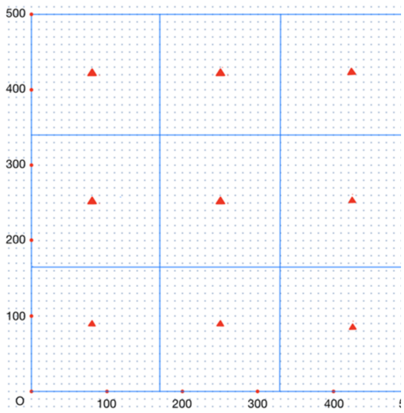

Figure 9. Nine UAV placement.

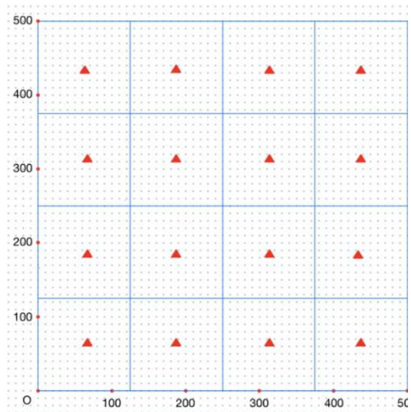

Figure 10. Sixteen UAV placement.

Having decided the distribution of B UAVs, we can now design the altitude of B UAVs through the chart shown in Fig. 11, which shows the relationship between the altitude of UAV and average channel power.

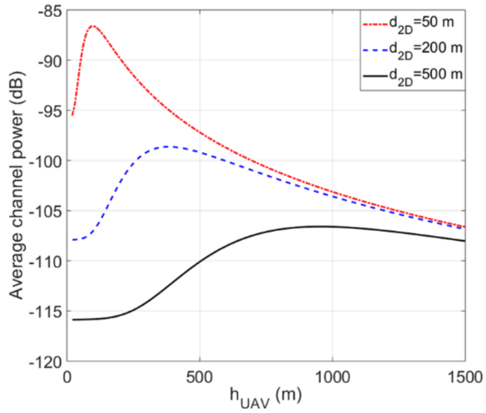

Figure 11. Average channel power versus the altitude of UAV.

The result turns out that the average channel power will be the best if h_{UAV} and d_{2D} follow the formula below:

$$h_{\mathrm{UAV}} = 2 \times d_{2D} \tag{18}$$

For d_{2D}, we can know from fig. 11. that the closer the distance between the user and the UAV, the better the Average Channel Power will be, so we only need to ensure that the farthest user in each case can get the better Average Channel Power, that is d_{2D} equals the distance from the furthest user to the UAV and we can calculate h_{UAV} separately according to the number of different UAVs. Then we can also calculate the altitude of UAV(A0) by using the same method in horizontal part above. The results of UAV's altitude are shown in Table 5.

Table 5. The results of UAV's altitude.

Number of UAV(B)	d_{2D}	Altitude of UAV(B)	Altitude of UAV(A0)
1	353.6m	707.2m	202.3m
2	395.3m	790.6m	/
4	176.8m	353.6m	717.0m
8	190.4m	380.8m	920.5m
9	117.9m	235.7m	835.3m
16	88.4m	176.8m	984.5m

Python has been used to simulate the random distribution of users, we calculated all parameters required for pathloss for each user, as mentioned above in formula 12 and also the farthest users' parameters as shown in Table 6.

Table 6. The parameters of farthest user.

Number of UAV(B)	θ / rad	d_{ref} / m	d_{los} / m
1	1.11	792.0	789.3
2	1.11	885.3	882.6
4	1.11	396.7	394.0
8	1.11	427.1	424.4
9	1.11	264.9	262.2
16	1.11	199.0	196.3

According to formula (1), (14) and the following formula:

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$$SNR = \frac{P_r}{P_n} \tag{19}$$

We calculated SNR and required SNR of each case. The results are shown in Table 7.

Table 7. Simulation of each case.

Number of UAV(B)	SNR / dB	Required SNR / dB
1	-0.95	22.54
2	5.86	22.54
4	11.10	22.54
8	13.46	22.54
9	18.16	22.54
16	23.16	22.54

According to Table 7, it can be seen that only when we set the number of UAVs(B) to 16 can we meet the SNR requirement of QPSK modulation mode. When we set the number of UAVs(B) to 16 and chose QPSK as the modulation mode, we can find a balance between bandwidth needed and number of UAVs needed.

5. Discussion

Through the establishment and analysis of solutions, we confirmed the possibility of using UAV swarm to provide communication service in disaster areas. We proved the feasibility of using OFDM and Beamforming with MATLAB simulation. Our solution effectively solved the problems of difficult deployment and low data rate of traditional solutions, with low cost and high data rate. Overall, our solution has great practical potential.

6. Suggestions for future work

This paper provides a special idea of using UAV as a relay station to provide communication services for people in disaster-stricken areas, while it will bring us some benefits. Firstly, we can effectively allocate bandwidth to adjust total usage, while the number of UAV carriers will be changed as the modulate of the height and the distance between two UAV. Secondly, compare to other UAV system, our new system will reduce the average power use, while we calculate the most suitable distance between each UAVs, therefore we will use less bandwidth and power. Finally, our idea can readily act as a base station, for they are easily to put at a suitable space， while improving communication to verify the universality for the future.

7. Conclusion

In our UAV relay system, we find out two of the modulation type can efficiently use less bandwidth and UAV— 16qam and QPSK. As can be seen from the previous text，when we increase the bit per symbol rate, we will use less bandwidth for each of the UAV. However, the number of UAV will be required more and more as the decrease of the bandwidth. These two types of modulation ideas can reduce the power use and UAV use at an appropriate number. It's worth noting that placing the UAV in the middle as multiple antennas can effectively improve the communication distance and reduce the number of UAVs. This is one of main methods to find the less bandwidth and less UAV.

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