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An Analysis of the Signal-to-Interference Ratio in UAV-based Telecommunication Networks

Hamid Jafaripour [1*], Mohammad Fathi [1]

[1.] Department of Electrical Engineering, University of Kurdistan, Sanandaj, Iran.

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Abstract

One of the most important issues in wireless telecommunication systems is to study coverage efficiency in urban environments. Coverage efficiency means improving the signal-to-interference ratio (SIR) by providing a maximum telecommunication coverage and establishing high-quality communication for users. In this paper, we use unmanned aerial vehicle (UAVs) as air base stations (BS) to investigate and improve the issue of maximizing coverage with minimal interference. First, we calculate the optimal height of the UAVs for the coverage radius of 400, 450, 500, 550, and 600 meters. Then, using simulation, we calculate and examine the value and status of SIR in UAVs with omnidirectional and directional antenna modes in symmetric and asymmetric altitude conditions, with and without considering the height of the UAVs. The best SIR is the UAV system with a directional antenna in asymmetric altitude conditions where the SIR range varies from 4.44db (the minimum coverage) to 52.11dB (maximum coverage). The worst SIR is the UAV system with an omnidirectional antenna in symmetrical height conditions without considering the height of the UAV. We estimate the range of SIR changes for different coverage ranges between 1.39 and 28dB. Factors affecting the SIR values from the most effective to the least, respectively, are coverage range and the antenna type, symmetrical and asymmetric height, and finally, considering or not considering the height of the UAV.

Keywords: base station; Telecommunication coverage; UAV; Signal-to-interference ratio.

1- Introduction

Mobile terrestrial communication systems are used with the help BS for mobile phone users, which has many problems such as high installation, maintenance and commissioning costs, lack of coverage of all points, especially obstacles and buildings, and lack of line of sight (LoS) communications [1]. UAVs are new tools, and their range of performance has expanded to include the next generation of telecommunications UAVs. UAVs offer better service as an alternative to ground-based stations because of the LoS connection between users and UAV stations. Due to UAVs' limitations, it is not practical to use them continuously and sustainably, and this should provide researchers with an ideal solution for maximum coverage. UAVs provide a cost-effective wireless connection for devices without infrastructure coverage. Compared to terrestrial communications or high-altitude-based operating systems (satellite communications), wireless systems with low-altitude UAVs are generally faster and configurable with more flexibility. They also have better communication channels due to direct vision communication [2].

With the continuous development of UAV in the communications and other related technologies, the UAV industry has developed rapidly in recent years. The 5G network also predicts significant growth in data traffic scale, number of terminal connections, high reliability, low latency and high transmission speed. With the advent of the 5G, this technology is expected to significantly increase the capacity and new applications for large-scale connections. The 5G wireless system is still terrestrial and has the same coverage complexity as other terrestrial networks. However, in the event of the destruction of terrestrial infrastructure due to sudden disasters, these land cover networks will be in place. They are damaged or even out of reach. The space communication network complements the terrestrial communication network. This can not only provide extensive communication coverage for people and vehicles at sea, remote rural areas and the air, but also provide timely network connections in the event of a ground network failure [3]. UAVs equipped

✉ **Hamid Jafaripour**
Hamid.jafaripour@uok.ac.ir

with radio receivers can meet the requirements of an air communication platform as a mobile base station or as an aerial relay. Due to their flexible deployment, UAVs can be used in multilayer mobile networks with the help of UAVs to provide on-demand communication services in disaster areas and increase the performance, capacity and reliability of existing terrestrial mobile networks. However, several challenges such as optimal 3D placement, flight endurance time, energy constraints, and interference management may hinder the widespread use of UAV communications [2]. In UAV communications, an air base station is primarily a low-altitude platform that can cover ground as UAV-based small cells (USCs). The size of USCs varies according to altitude, position, transmission power, type of UAVs and environmental characteristics. Given this, the optimal placement of UAVs for USC cap performance analysis has attracted much research interest. For example, in [4-5], the UAV deployment problem is considered to increase the coverage of a single USC. Analysis probability for signal-to-noise ratio (SNR) thresholds were analyzed. In [8] they analyzed the problem of optimization for UAV placement to increase the number of users covered by different quality of service (QoS). However, this has been done for single-UAV networks. When multiple UAVs are available, [9-10] exploit the deployment of multiple UAVs to reduce the number of air BSs and expand coverage for ground users. In addition, most works optimize the horizontal coordinates of the UAVs for a fixed UAV height above ground level [11] or, while having a fixed horizontal position [12-13] optimize the UAV height. These studies analyzed the UAV location using an optimization framework in a non-interference environment. The ratio of the area covered and the area given is usually a measure of the UAV network coverage capability [14]. In addition, by adding influential factors in the mission area, it makes the ability to cover more specific and accurate.

About the environment and reduction of communications and flight overhead in order to avoid severe consequences, it has been pointed out that under the influence of UAV cooperation, the UAV cover mission can be performed well. However, Multi-UAV is rarely studied because it is difficult to describe a collaborative relationship. In the paper, the coverage area and signal to interference experienced by users at a UAV-enabled network is investigated against different configurations of antenna and UAV heights. Most common configurations in this network including antenna type in terms of omnidirectional and directional, antenna height, and UAV locations are examined numerically for their impacts on the network performance.

The paper is organized as follows. Research done in the area is given in Section 2 as literature review. The adopted network model of UAVs and the employed channel modes are presented in Section 3. Achieved results and detailed discussions are presented in Section 4, and the paper is concluded in Section 5.

2- Literature Review

Research has been done to investigate the problem of UAV coverage. In [15], by designing a paradigm that considers the energy consumption and communication power of the UAV, authors examined the relationship between the low-consumption UAV and a ground terminal and also defined the energy efficiency of the UAV communication. In [16], the probability function of the coverage for the ground user was extracted from a given UAV, which consists of increasing the antenna and altitude. In terms of UAV communications, various tasks have been proposed to describe the interference created by UAVs. A multi-dimensional multi-UAV deployment approach has been proposed to meet the QS requirements for different types of user distribution in the presence of common channel interference by maximizing the minimum achievable throughput for all ground users [17]. Investigates the interference characteristics of UAVs equipped with directional antennas in three-dimensional space in done in [18]. A cooperative beam forming technique is proposed for the BS to reduce the strong interference caused by common ground channel transmissions to the UAV in [19]. The problem of reducing interference and resource allocation in a wireless communication system, with two UAVs and two ground nodes has been investigated in [20]. Investigated the maximization of coverage in the presence of co-channel interference (CCI) generated by several UAVs in a specific target area in done in [21]. Authors in [22] investigate the effects of interference in urban environments for four-engine UAVs based on inter-carrier interference (ICI) and inter-symbol interference (ISI), which arise from multi-route scenarios. Minimizes signal-to-interference-plus-noise ratios (SINR) among all UAVs by jointly optimizing channel and power allocation strategy under severe resource availability is done in [23]. Authors studies the interaction of two UAV-enabled users for wireless powered communication networks in [24].

Authors in [25] propose a three-dimensional coordination model for interference management through the formation of the multicellular beam in multi-antenna UAV networks. The work in [26] offers an adaptive interference cancellation (IC) approach in which each BS can decrypt terrestrial user messages by adaptive switching between IC modes. Authors in [27] explains the main concept of high-power microwave (HPM) pulse interference and examines the possibility of electromagnetic interference against UAVs. Increased variability in cut-off probability and SNR in a multi-UAV network in the presence of interlink UAVs and cellular BSs has been investigated in [28].

Authors in [29] examines the key challenges of UAV-based radio scanner measurements to evaluate 5G aerial emissions to manage interference in non-public networks. Authors in [6] proposes a scheme for non-orthogonal multiple access (NOMA) in UAV communication systems in the presence of granted and un-granted users. Fast machine learning is presented for 5G beam selection for unmanned aerial vehicle applications in [7].

3- Mathematical Model

Small cells. Therefore, the main challenge to be addressed is maximizing UAV coverage in the presence of interference. It is evident from the Channel model that if there is no coordination between the UAVs, we will face interference problems and interference. If the distance between adjacent UAVs is too large, parts of the urban environment will not be covered. Also, if this distance reduces, it will lead to overlap of different areas. This causes severe interference of the channels (especially in the case that all sides use the same frequency). In UAV communications, co-frequency interference occurs when multiple UAVs share the same frequency sources simultaneously in separate space locations.

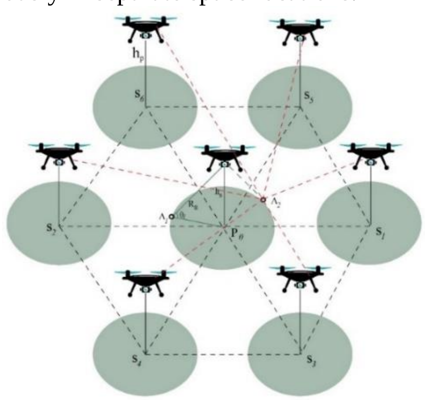

Fig. 1. Primary and secondary UAVs placement and user interference at the primary UAV's cell border

In this paper, we have used a multi-UAV synchronized network to reduce co-frequency channel interference in UAV communications. We assume a general multi-UAV model for M air BSs. The initial UAV is stationary and located above the center of the specified target surface. This UAV acts as a reference node to adjust the separation distance while the secondary UAVs are in proportion to the location of the primary UAV. After optimization, we place the secondary UAVs in a fixed position to fix their coverage area on the ground. Primary and secondary UAVs are located at $\boldsymbol{h_p}$ and $\boldsymbol{h_s}$ altitudes, respectively. According to Figure 1, we consider seven UAVs in the target area (square) with a side length of L= 2000 meters in a two-dimensional Cartesian system. We can use this model for any number of UAVs, but in practice a large number of UAVs complicates the calculations.

In this case, P_0 is the image center of the primary UAV and S_1 ,..., S_{M-1} are the coordinates of the secondary UAV. In addition, we can deploy coordinated multi-UAV networks on the basis of a regular convex polygon design to meet the required coverage at the target level with the required number of UAVs. Among all the possible possibilities of interference, we examine the worst type of interference, i.e., interference at the cell boundary of the primary UAV by the secondary UAVs shown in Figure 1. We focus on the use of quasi-stationary UAVs. The position of the UAVs remains unchanged for a specified period of time. For such settings, it is important to determine the coordinates of the UAVs to avoid collisions between them. To control interference, we must create spatial separation between the UAVs. Therefore, in the deployment strategy, we assume that the initial UAV is in the position P0 = {0,0}. When M = 7, we plot the coordinates of the secondary UAVs in a hexagonal pattern as in Figure 1[21].

$$S_x = \begin{cases} S_1, & ((D_{min}+D), O) \\ S_2, & (-(D_{min}+D), O) \\ S_3, & (\frac{1}{2}(D_{min}+D), -\frac{\sqrt{3}}{2}(D_{min}+D)) \\ S_4, & (-\frac{1}{2}(D_{min}+D), -\frac{\sqrt{3}}{2}(D_{min}+D)) \\ S_5, & (\frac{1}{2}(D_{min}+D), \frac{\sqrt{3}}{2}(D_{min}+D)) \\ S_6, & (-\frac{1}{2}(D_{min}+D), \frac{\sqrt{3}}{2}(D_{min}+D)) \end{cases} \quad (1)$$

here D_{min} is the minimum separation distance to avoid collisions between the UAVs and to ensure minimum coverage performance for all participating UAVs in the presence of interference. In this case, D is the only variable that controls the performance of the coating surface between a target surfaces.

3-1- Channel Model

In this model, the main communication components as shown in Figure 2 include ground BS, BS UAV, and ground users. We have divided the channels according to the type of connection of the main units. Generally, there are four types of channels: A2G channels, ground-to-air (G2A) channels, air-to-air (A2A) channels, and ground-to-ground channels. In this article, we examine only the A2G channel (UAV to the user).

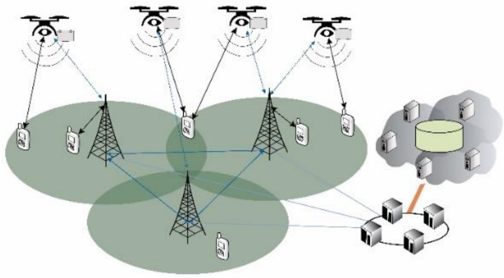

Fig. 2. The main components of the communication network

In general, the UAV propagation channel to the user is usually modeled separately with the possibility of LoS and NLoS occurring. NLoS links have more path loss than LoS links due to the effect of shadow and signal reflection from obstacles. The probability that UAV(i) communicates LoS with user(j) is calculated as follows [10],[23]:

$$P_{(LoS,UAV,User)}=\frac{1}{1+\alpha(\exp(-\beta(\theta_{User}-\alpha))} \quad (2)$$

where α and β are fixed values that depend on the environment (dense and non-dense regions). θ_{User} is the angle between the UAV(i) and the user(j). $\theta_{User} = \frac{180}{\pi\, tanh\,(h/r)}$, h is the altitude of the UAV, and r is the ground distance between the UAV(i) and the user(j). We calculate this distance as below:

$$r=\sqrt{(X_{User}-X_{UAV})^2+(Y_{User}-Y_{UAV})^2} \quad (3)$$

here X_{UAV} and Y_{UAV} are the position and coordinates of the UAV; X_{User} and Y_{User} are the position and coordinates of the ground users. In the urban environment, UAVs are located without intermediaries and with the shortest distance from the users in the coverage area. Due to the dynamics of the UAVs, the barriers do not prevent LoS from communicating with ground users. As a result, the chances of establishing an NLoS are very little. Given the above, we will skip the NLoS computing in the urban environment. Therefore, the total path loss is equal to the path loss in LoS mode and is calculated based on the following equation:

$$L_{Total}=L_{Los}=\eta_{Los}\,(4\pi\frac{f}{c})^2\,R^2 \quad (4)$$

where f is he carrier frequency, c is the speed of light, η_{Los} (in db) is the loss related to the LoS connection of the environment, and R is the direct distance between the UAV(i) and the user(j)which is calculated according to the following equation:

$$R=\sqrt{r^2+h^2} \quad (5)$$

3-2- UAV Height Calculations

The deployment of primary and secondary UAVs is divided into two categories, symmetric and asymmetric, according to Figure 3. In symmetrical mode, the altitude and transmission power of all UAVs (primary and secondary UAVs) are the same.

However, for asymmetric cases, the primary UAV is placed at the desired height and the secondary UAVs can be placed at a height higher or lower than the height of the primary UAV. In this paper, we will calculate the effects of symmetric and asymmetric heights on the degree of interference in the urban environment in different conditions. By introducing different coverage areas, in addition to the minimum interference, we have also examined the maximum coverage. We have introduced D as the variable parameter to determine the coverage range of the UAVs, D_{min} as the minimum separation distance to avoid collisions between the UAVs. According to Figure 1, the different values of D and D_{min} can be calculated based on the following equation:

$$3D+2D_{min}=2000\text{m} \quad (6)$$

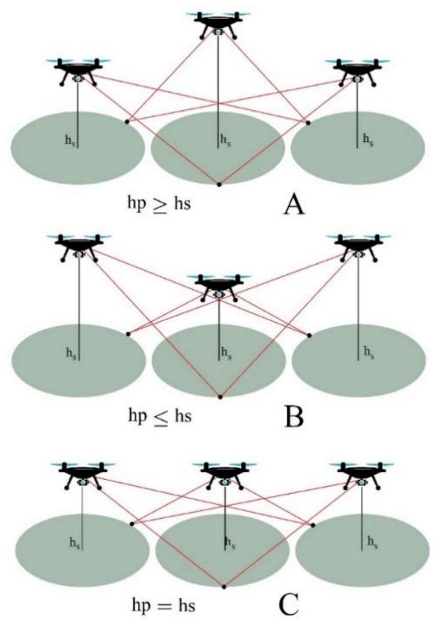

Fig. 3. a and b: The UAVs' heights in asymmetric conditions.
c: The UAVs' heights in symmetrical conditions

If we set the value D = D_{min}, we will have the minimum coverage and maximum security between the UAVs, in which case the value of D is equal to 400m. We calculate the optimal values of D and D_{min} and put them in Table 1. The appropriate height of the UAV to cover area D (based on the UAV antenna angle), which can cover the area from an angle of 0 to 60 degrees, is calculated from the following equation:

$$h = r * \tan 30 = 200 * \left(\frac{\sqrt{3}}{2}\right) = 115\ m \quad (7)$$

At D= 400m we have the minimum coverage and D= 600m the maximum coverage. Our goal is to maximize coverage area with minimum interference and the number of UAVs.

Table 1. D and D_{min} values and optimal height and distance of the cell border user from the UAV

D	400	450	500	550	600
$\boldsymbol{D_{min}}$	400	325	250	175	100
Optimal Height	115	130	145	159	173
User Distance	230	450	288	318	346

4- Results and Discussion

In this paper, the effects of antenna type (all-purpose antenna and directional antenna) and the conditions of the height of the primary and secondary UAVs relative to each other (symmetrical and asymmetric) and with and without considering the height of the UAVs on the SIR are investigated. Regardless of the height of the UAV, the user distance of the primary UAV cell border to the center point of the secondary UAV cell is calculated as the ground distance and the effect of the height of the secondary UAV is not counted, but in the case of altitude, the height of the UAVs is also calculated.

4-1- Analyzing the SIR of Directional Antennas with Symmetrical Height, without Considering the UAVs' Heights

We consider the user at the cell boundary of the primary UAV as shown in Figure 1, which receives telecommunication services by UAV S1. We have not first applied the effects of UAV height on user interaction in the equation. Assuming that the user of the primary UAV cell border is receiving fixed frequency telecommunication services from the primary UAV and UAVs S2 to S7 are sending data to users inside their cell with the same operating frequency.

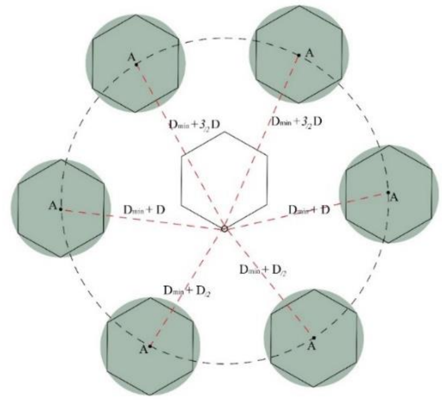

Fig. 4. The effect of secondary cell interference on the user at the primary cell border

In this situation, S2 to S7 UAVs affect the user performance at the S1 UAV cell boundary and interfere. The ratio of the received signal power (S) to the interference power received from the environment is called SIR. SIR affects QoS and determines the bit error rate. The SNR is calculated from the following equation:

$$\text{SIR} = \frac{S}{I} = \frac{KP_{tp}d^{-\gamma}}{\sum_{n=1}^{N} KP_{tn}{d_n}^{-\gamma}} \quad (8)$$

where K is a constant value and γ is a value between 2 and 4. P_{tp} is the transmitting power of the primary UAV, d is the distance between the UAV and the user, P_{tn} is the transmitting power of each of the secondary UAVs and d_n is the distance of each of the secondary UAVs relative to the user of the primary UAV cell boundary.

The simplified interference of the secondary UAVs relative to the user at the cell boundary of the primary UAV as shown in Figure 4 is as follows:

$$\text{SIR} = \quad (9)$$

$$= \frac{\left(\frac{D}{2}\right)^{-4}}{2\left(D_{min} + \frac{D}{2}\right)^{-4} + 2\left(D_{min} + \frac{3D}{2}\right)^{-4} + 2(D_{min} + D)^{-4}}$$

$$= \frac{1}{2(\frac{2D_{min}}{D} + 1)^{-4} + 2(\frac{2D_{min}}{D} + 3)^{-4} + 2(\frac{2D_{min}}{D} + 2)^{-4}}$$

In Figure 5, for the primary UAV we consider D= 400m and for the secondary UAV, all default values of D (450, 500, 550 and 600m) to calculate the optimal SIR value. In this case, the size of the D_{min} distance between the UAVs is the maximum value, so the SIR value at D = 400m has the maximum possible value. But the main problem of the coverage range D = 400m is the minimum telecommunication coverage, which has the most non-coverage of areas. As D increases, D_{min} decreases and SIR decreases.

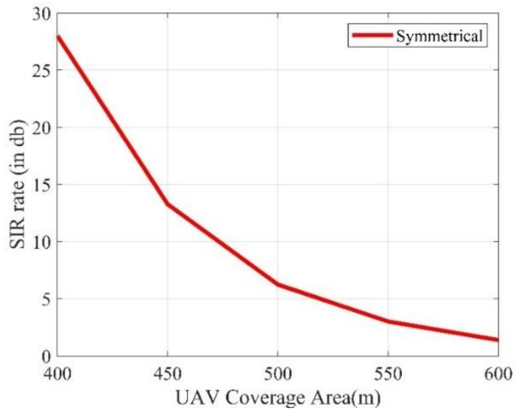

Fig. 5. Estimating SIR based on D in terms of symmetric altitude of UAVs

The coverage level ratio determines the overall performance of the coverage level in the desired multi-UAV system. On the other hand, in particular, the ratio of the total effective surface covered by the primary UAV and the secondary UAV to the target surface is defined. This ratio can be calculated from the following equation[21]:

$$A_C(D) = \frac{2}{L^2}\left[\int_0^{R_P(D)} \int_{\emptyset_P}^{\emptyset_P=\pi} Rd\, Rd + (M-1) \; * \int_0^{R_S(D)} \int_{\emptyset_S}^{\emptyset_S=\emptyset_{max}} Rd\, Rd\emptyset \right. \tag{10}$$

Where L2 is the target surface area desired in the system model. $\emptyset_{max}$ is the coverage of secondary UAVs and is calculated as follows:

$$\emptyset_{max} = \pi - \arccos\left\{\frac{D_{min} + D}{R_S}\right\} \tag{11}$$

Through equations 10 and 11, we calculated the coverage rate in the environment with symmetrical height (Table 2). Table 2. The coverage rate based on the function of D and D_{min} in UAV symmetric altitude ($h_s = h_p$)

Table 2. The coverage rate based on the function of D and D_{min} in UAV symmetric altitude ($h_s = h_p$)

D	***D_{min}***	***h_p***	***h_s***	***Coverage Rate***	***Coverage percentage***	***The Surface without Service***
400	400	1250	1250	879646	21.99	3120354
450	325	1400	1400	1113302	27.83	2886698
500	250	1570	1570	1374447	34.36	2625553
550	175	1727	1727	1663080	41.57	2336920
600	100	1880	1880	1979203	49.48	2020797

According to Table 2and Figure 6, we found the appropriate coverage area and the desired SIR value, then we designed and implemented the UAV network based on it.

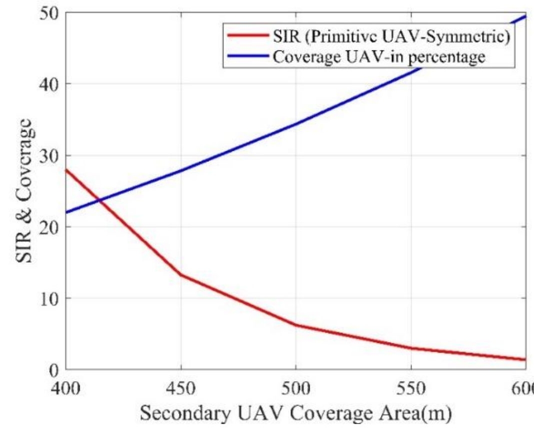

Fig. 6. Estimating the SIR and coverage area based on D in UAVs' symmetrical altitude conditions

4-2- Analyzing the SIR of Directional Antennas with Symmetrical Height Considering the UAVs' Heights

In this case, according to Figure 7, we have included the height of the UAV in the intercellular interference problem, and the new conditions for calculating the SIR has changed as follows:

$$SIR = \frac{(\frac{D}{2})^{-4}}{2(L_1)^{-4} + 2(L_2)^{-4} + 2(L_3)^{-4}} \tag{12}$$

$$L_1 = \sqrt{(D_{min} + D)^2 + (h_s)^2} \tag{13}$$

$$L_2 = \sqrt{(D_{min} + \frac{D}{2})^2 + (h_s)^2} \tag{14}$$

$$L_3 = \sqrt{(D_{min} + \frac{3D}{2})^2 + (h_s)^2} \tag{15}$$

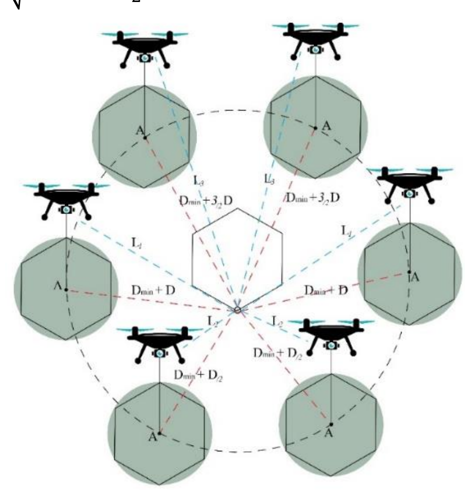

Fig. 7. The Effect of secondary cell interference on the user at the primary cell border considering the height of the UAV

Figure 8 shows the SIR status in symmetric altitude conditions, considering the height of the UAV. This case acts like a situation when the height of the UAV is not considered, and in areas with high coverage and fewer cell separation distances, system status and user coverage will be problematic.

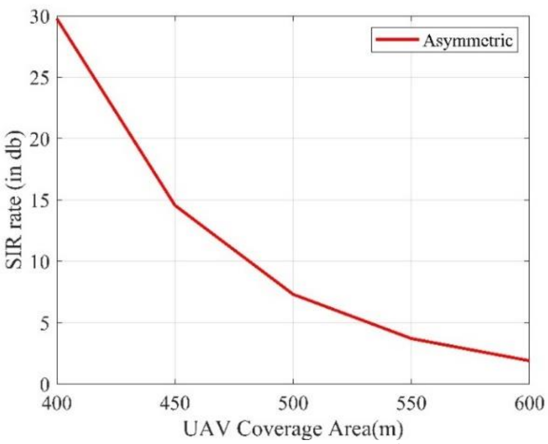

Fig. 8. Estimating the SIR based on D in terms of symmetric heights of UAVs considering the UAVs heights

The effects of secondary UAV signals on user performance at the primary cell border in both conditions with and without considering the height of the UAV are shown in Figure 9. The blue color indicates SIR considering the height of the UAV and the red color indicates SIR regardless of the height of the UAV. The overall condition of the SIR is better in terms of UAV altitude, but in both conditions, there is extensive coverage of the poor quality of customer service at the cell border. The rates of area coverage in conditions regardless of the UAV and considering the UAVs are equal.

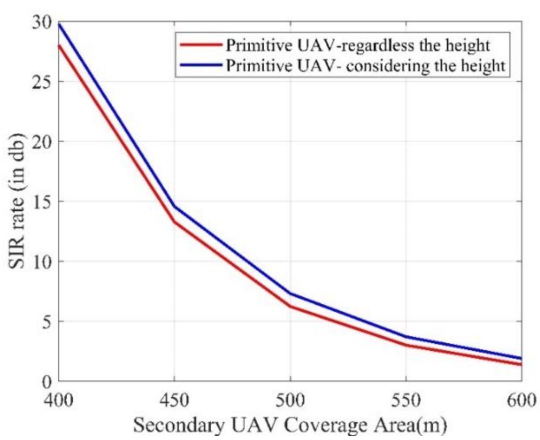

Fig. 9. SIR at symmetrical altitude conditions with and without UAV altitude

4-3- Analyzing the SIR of Omnidirectional Antennas with Asymmetric Height without Considering the UAVs' Heights

When UAVs fly in different classes with asymmetric heights in the urban environment, the goal is to reduce interference and transmit power to have high quality communication. The effect of height on the interference of the urban environment is very obvious. UAVs can be located at the desired and optimal height and continue to provide services in a situation where the number of active users in a cell to receive services is less than its coverage capacity. However, if for humanitarian reasons such as marches, reopening of shopping malls, etc., the number of active users is more than the UAV coverage capacity, based on the amount of demand, other devices help the UAV to get maximum user coverage. The difference is that the height of the UAVs is lower than the non-crowded conditions and their coverage area is also reduced. In this case, the initial UAVs are first placed at the desired height and optimal h_p.

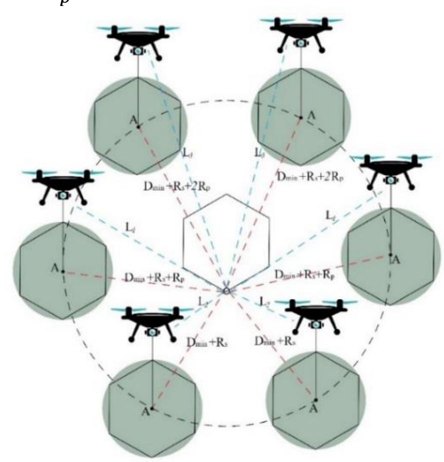

Fig. 10. The effect of secondary cell interference on the user present at the primary cell boundary considering the height of the UAV

The secondary UAVs are then placed at the optimum altitude of h_s relative to the primary UAVs. Therefore, the first goal is to place the initial UAVs at the desired h_p altitude to achieve maximum user coverage in the urban environment. Optimal UAV height selection and proper antenna angle selection minimize interference, reduce transmission power, and increase SIR. For example, if the initial UAV is to cover the D = 500m range, consider other D values (400, 450, 550, and 600m). In this case, in the values of D = 400/450m, the height of the primary UAV is higher than the secondary UAV, in other words: $h_p \succ h_s$. At values D = 550/600m the height of the primary UAV is less than the secondary UAV ($h_p \prec h_s$).

The grond distance of the center of the secondary UAVs relative t the user at the primary cell boundary (Figure 10) is calculaed from the following equation:

$$SIR_{DP,DS} = \frac{(R_p)^{-4}}{2(D_1)^{-4} + 2(D_2)^{-4} + 2(D_3)^{-4}} \quad (16)$$

$$D_1 = D_{min} + R_s + R_p \quad (17)$$

$$D_2 = D_{min} + R_s \quad (18)$$

$$D_3 = D_{min} + R_s + 2R_p \quad (19)$$

$$D_{min} = 1000 - 2R_s - R_p \quad (20)$$

According to Figure 11, the larger is the coverage area of the initial UAV, the lower is the SIR of the network. The red lines indicate the primary cell with D = 600m, which has the lowest SIR value. This range is even lower than the conditions when the primary UAV is D = 400,450,500m and the secondary UAVs are at D = 600m and causes many problems for users' performance in this range.

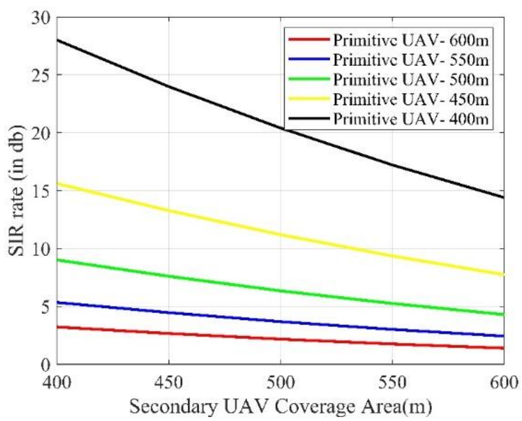

Fig. 11. Analyzing the symmetric interference regardless of the UAVs' heights

For the initial UAV's cover values D = 500, 550,600m, the SIR value is lower than the acceptable threshold for providing communication services to cell border users and the communication link either is not established or has poor quality communication links. In situations where the primary UAV has a value of D = 450m, the coverage ranges of the secondary UAVs provide an acceptable threshold of D = 400, 450m. For D = 500, 550, 600m it is not possible to provide an acceptable minimum threshold, but the condition of the UAV network will be much better than the initial UAV modes D = 500, 550, 600m. If the primary UAV has a coverage range of D = 400m, it will provide a quality link for all D values as areas covered by the secondary UAV.

The UAV's coverage rate in different conditions of primary and secondary UAV deployment can be calculated through Equations 12 and 13. According to Figure 12, the highest value of coverage and the lowest value of SIR are provided by the initial UAV with D=600m and the lowest area coverage is related to D=400m, which provides the best quality of service for users. To get the optimal value, you have to choose the middle ground between different values of D.

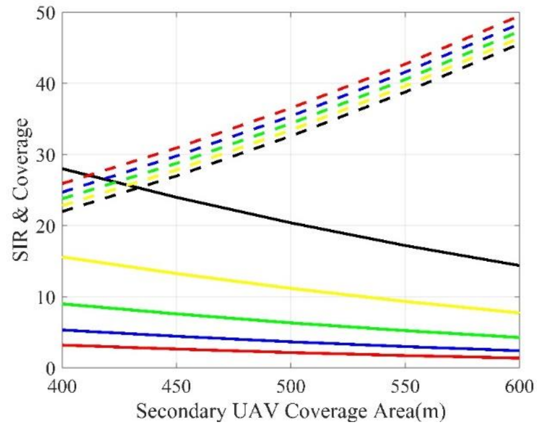

Fig. 12. Estimated SIR (red, blue, green, yellow, and black lines, respectively, for initial UAV coverage with values of 400, 450, 500, 550, and 600 meters) and the coverage area based on D (continuous lines) in the condition of asymmetric height of UAVs.

4-4- Analyzing the SIR of Omnidirectional Antennas with Asymmetric Height without Considering the UAVs' Heights

The interference is calculated by considering the height of the secondary UAVs to the user at the primary cell boundary based on the following equations:

$$L_1 = \sqrt{(D_{min} + R_s + R_p)^2 + (h_s)^2} \quad (21)$$

$$L_2 = \sqrt{(D_{min} + R_s)^2 + (h_s)^2} \quad (22)$$

$$L_3 = \sqrt{(D_{min} + R_s + 2R_p)^2 + (h_s)^2} \quad (23)$$

$$SIR_{Dh,Ds} = \frac{(R_p)^{-4}}{2(L_1)^{-4} + 2(L_2)^{-4} + 2(L_3)^{-4}} \quad (24)$$

As shown in Figure 13, there are many functional similarities between asymmetric systems with and without UAV height.

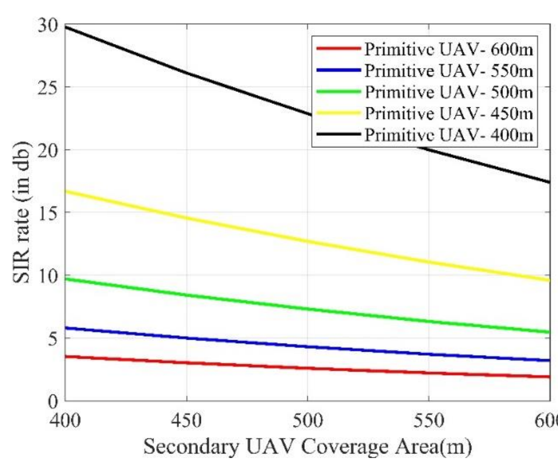

Fig. 13. Analyzing the asymmetric SIR considering the UAV's height

As we move away from D= 400m and move towards D = 600m, the coverage range gradually increases and the SIR gradually decreases, which can be explored between different values of D to find an area with a suitable coverage range and a desirable SIR.

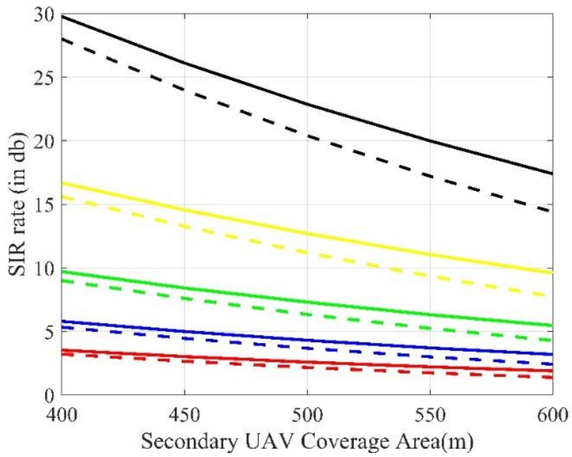

Fig. 14. Comparison of asymmetric SIR considering the height of the UAV (red, blue, green, yellow and black lines respectively for the initial UAV coverage with values of 400, 450, 500, 550 and 600 meters) and without the height of the UAV (continuous lines).

Figure 14 compares SIRs between asymmetric systems with and without UAV heights, which are similar in performance. SIR performance in an asymmetric system considering the height of the UAV at all D values is better than the asymmetric system without considering the height of the UAV. In the primary UAV area with D= 450m and secondary D = 550m, which did not receive the acceptable minimum SIR threshold in the system without considering the UAV height, in the system, considering the UAV height, received the desired threshold. Also, in the primary UAV with D = 500m and the secondary D = 400m, it is close to the desired threshold and has an acceptable value compared to the system, regardless of the height of the UAV. Other cases are equal in terms of SIR threshold and area coverage.

4-5- Analyzing the SIR of Directional Antennas with Symmetrical Height without Considering the UAVs' heights

In omnidirectional antennas, the wave propagation angle is only 360 degrees, while in directional antennas, the angle can be selected between 0 and 360 degrees. Normally, the angles of 60- or 120-degree directional antennas are selected, which have already been studied in terms of system and efficiency and have received appropriate results.

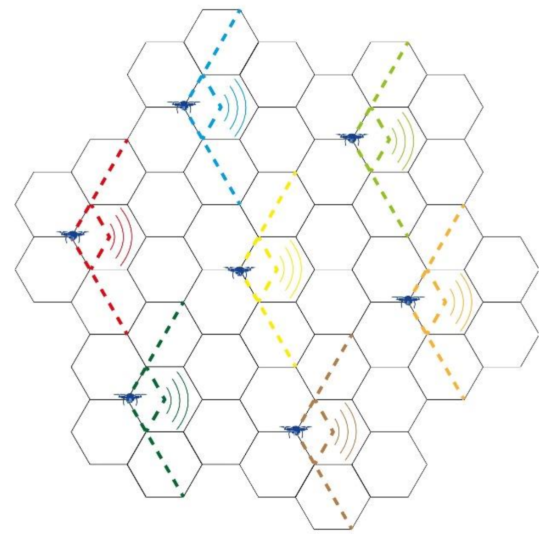

Fig. 15. Using a unidirectional antenna mounted on a UAV in a two-dimensional space of an urban environment

The directional antenna can reduce interference and blur and improve the quality of communication by concentrating the transmitted energy in one direction. We have installed antennas with 120-degree angles on the UAVs. The number of UAVs that affect the user at the cell boundary of the primary UAV if all-round antennas are used is at least 6 UAVs.

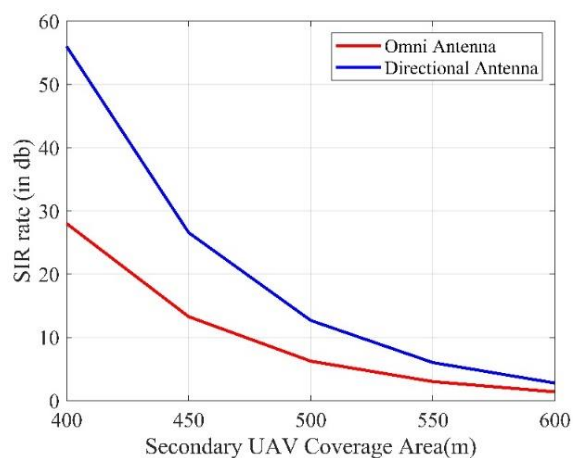

Fig.16. The comparison of SIR with and without directional antenna in symmetrical UAVs conditions without applying UAVs' heights effects

We have installed antennas with 120-degree angles on the UAVs. The number of UAVs that affect the user at the cell boundary of the primary UAV if all-round antennas are used is at least 6 UAVs. By using one-way antennas according to Figure 15 and considering the position of the UAVs relative to the cells, the interference is reduced to 3 UAVs and we have eliminated 50% of the network interference with this action. In one sentence, the use of a one-way antenna with an angle of 120 degrees maximizes interference in the urban environment and the power consumption for data transmission to a minimum and the quality of communication. The amount of SIR in the direction of using the directional antenna is calculated from the following equation:

$$SIR = \frac{S}{I} = \frac{1}{(\frac{2D_{min}}{D}+1)^{-4} + (\frac{2D_{min}}{D}+3)^{-4} + (\frac{2D_{min}}{D}+2)^{-4}} \quad (25)$$

SIR function using directional antenna has the same function as omnidirectional antenna and has the maximum SIR value at D = 400m and at any distance from D = 400m and moving towards D = 600m, the SIR value gradually decreases (Figure 16). By using directional antenna in all D values, SIR has a better situation than all-purpose antenna conditions and has improved network condition and service quality.

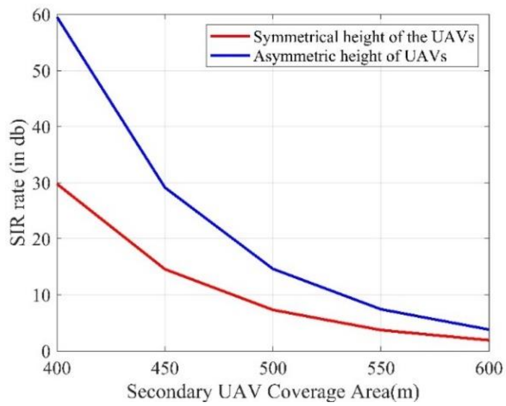

Fig.17. Comparing the SIR with and without directional antenna in symmetrical UAV conditions with UAV altitude effects

4-6- Analyzing the Directional Antenna's SIR with Symmetrical Height, Considering the UAVs' Heights

The SIR values in directional antenna conditions with symmetrical height, considering the UAVs' heights are calculated based on the following equation:

$$SIR = \frac{(\frac{D}{2})^{-4}}{(L_1)^{-4} + (L_2)^{-4} + (L_3)^{-4}} \quad (26)$$

In the above equation, L1, L2 and L3 can be calculated from equations 12, 13 and 14, respectively.

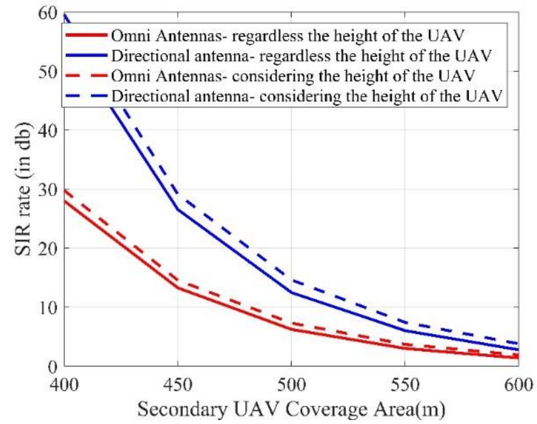

Fig. 18. The comparison of SIR with and without directional antenna in symmetrical UAVs conditions with UAV altitude effects

Figure 18 shows an overview of the SIR situation in terms of the use of symmetric UAVs, which was the lowest absolute SIR to symmetric UAVs with all-round antennas, regardless of the height of the UAVs.

4-7- Analyzing the SIR in Directional Antennas with Asymmetric Height without Considering the UAVs' Heights

The SIR values in directional antenna conditions with asymmetric height, without considering the UAVs' heights are calculated based on the following equation:

$$SIR = \frac{(\frac{D}{2})^{-4}}{(L_1)^{-4} + (L_2)^{-4} + (L_3)^{-4}} \quad (27)$$

The values of L_1 , L_2 and L_3 can be calculated from equations 21, 22 and 23, respectively. In Figure 19, the smaller the radius of coverage of the original UAV, the smaller the coverage range. But the SIR will be at its highest, and vice versa .

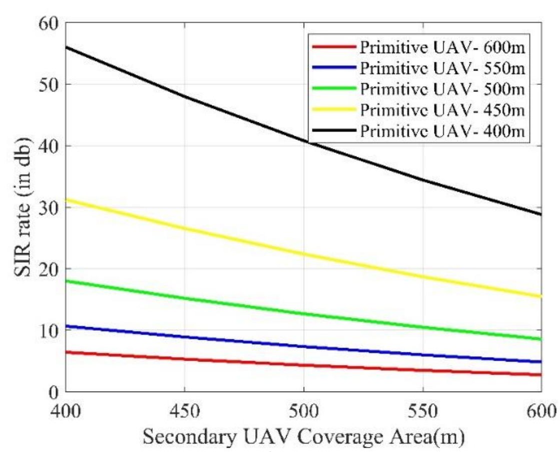

Fig. 19. Analyzing the SIR of asymmetric UAVs using directional antenna without applying UAV Altitude effects

The most important factor that determines the amount of SIR in an asymmetric network is the amount of coverage area D of the primary UAV. Selecting different values of D changes the amount of SIR on a large scale and creates a large jump in the dimensions of SIR, which is a significant difference between SIR with values of 400 and 600m.

To access the desired SIR, we must first calculate and select the optimal range of the initial UAV, which has the greatest impact on link quality. Then we select the optimal value of the area covered by the secondary UAV, which is the range of SIR improvement in a specific and limited range and has a much less effect than the coverage range of the primary UAV. To better understanding of the performance of directional antenna and omnidirectional antenna at asymmetric altitude conditions between the primary and secondary UAVs, we must compare the performance between them, which is illustrated in Figure 20. In general, the SIR performance of a directional antenna is significantly better than an omnidirectional antenna, providing better performance and a better communication link for all D values.

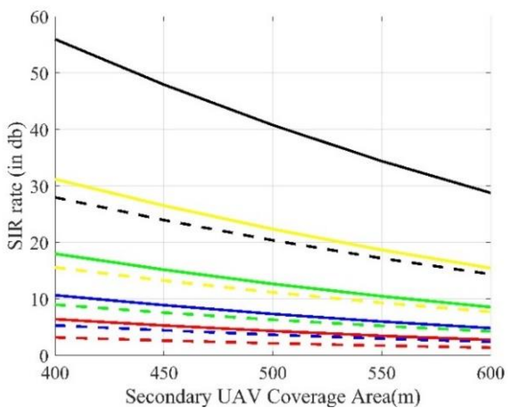

Fig.20. Analyzing the SIR in symmetric UAVs using directional antennas (red, blue, green, yellow and black lines respectively for the initial UAV coverage with values of 400, 450, 500, 550 and 600 meters) and omni-directional antennas (continuous lines) without applying the effects of UAVs' heights.

4-8- Analyzing the SIR of Directional Antennas with Asymmetric Height, without Considering the UAVs' Heights

The SIR values in directional antenna conditions with asymmetric height, without considering the UAVs' heights are calculated according to the following equation:

$$SIR_{DH,DP} = \frac{(R_p)^{-4}}{(L_1)^{-4} + (L_2)^{-4} + (L_3)^{-4}} \quad (28)$$

According to Figure 21, we conclude that the effects of selecting the coverage range D for the initial UAV had the greatest effect on the SIR. The larger the coverage range of the initial UAV, the higher the SIR value and the better the link quality. The red lines indicate the primary cell with D = 600m, which has the lowest SIR value.

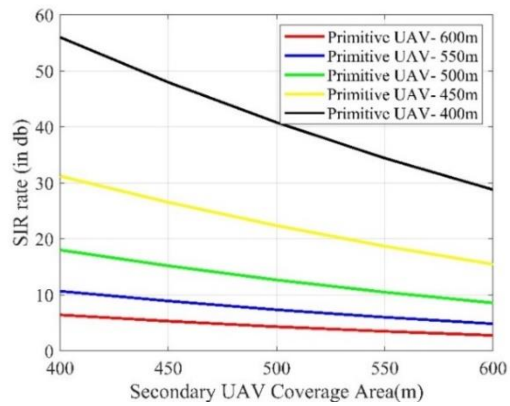

Fig. 21. Investigating the SIR of asymmetric UAVs using a directional antenna by applying the effects of the UAV height

The SIR value is lower in the condition that the coverage range of the primary UAV is D = 600m, even compared to the condition when the primary UAV is D =400, 450 and 500m and the secondary UAV is D=600m, and causes many problems for users in this range. In the coverage range of the initial UAV with D = 600m, the SIR value is below the acceptable threshold for providing communication services to cell border users and the communication link is not established or the communication is of poor quality. In case the primary UAV has a value of D = 500m, it has provided an acceptable threshold for the coverage ranges of the secondary UAVs D = 400/450m and for D = 500,550 and 600m it has not been able to provide an acceptable minimum threshold. For other D points for the primary UAV an acceptable threshold is provided for all coverage areas D for the secondary UAV. The best case in this situation is the primary UAV with D = 500m and the secondary UAV with D = 600m.

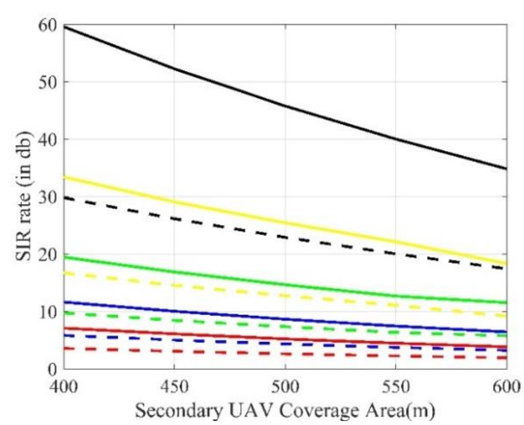

Fig. 22. Analyzing the SIR in asymmetric UAVs using directional antennas (red, blue, green, yellow and black lines respectively for the initial UAV coverage with values of 400, 450, 500, 550 and 600 meters) and omni-directional antennas (continuous lines) with applying the effects of UAVs' heights.

Figure 22 examines the SIR of UAVs with omnidirectional and directional antennas, considering the heights of the UAVs. In general, we notice that the network's SIR in the directional antenna is better than that of the omnidirectional antenna.

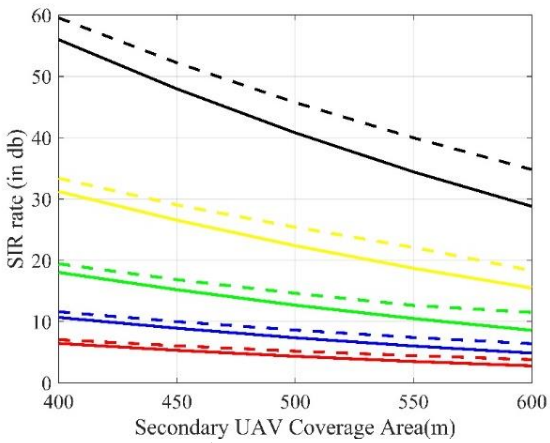

Fig. 23. The comparison of SIR using directional antenna in symmetric UAV conditions with (red, blue, green, yellow and black lines respectively for the initial UAV coverage with values of 400, 450, 500, 550 and 600 meters)/without (continuous lines) applying the effects of UAVs' height.

Figure 23 compares the SIR between asymmetric systems using directional antennas with and without considering the heights of the UAVs, which are very similar in terms of performance. Finally, we have put the optimal SIR values in the use of omnidirectional and pointed antennas, with and without considering the height and symmetric and asymmetric height in Table 3.

Table 3. Optimal SIR Values for Different D Conditions

Secondary Optimal D	***Primary Optimal D***	***UAVs' Height Calculation***	***UAVs' Height***	***Antenna Type***
450	450	Without height	Sym	Omni
450	450	With height	Sym	Omni
550 600	500 450	Without height	Asym	Omni
600 550	400 450	With height	Asym	Omni
500	500	Without height	Sym	direct
500	500	With height	Sym	direct
550 600	500 450	Without height	Asym	direct
600 450	500 550	With height		direct

*Sym= Symmetric and Asym= Asymmetric
Omni= Omnidirectional and direct=directional

5- Conclusions

In this paper, the coverage area and signal to interference experienced by users at a UAV-enabled network were investigated against different configurations of antenna and UAV heights. The optimal options have been achieved using extensive numerical computations. In overall, three factors affect the improvement of the coverage area and SIR. The first and the most effective factor is choosing the type of antenna. The directional antenna has a better SIR in all coverage areas than the omnidirectional antenna. The second factor on SIR is the symmetric and asymmetric height of UAVs. After calculations, we found that asymmetrical systems achieved a better SIR than symmetrical systems. The third factor with the least impact on the amount of interference is the height of the drone, which has a very small impact on the system performance. For more comparison, we also estimated the situation without considering the height of the drone, which results in no system performance improvement. Finally, the best SIR condition related to the system is the directional antenna, asymmetric height, and considering the height of the UAVs.

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