Centralized Interference Coordination of Cluster heads for UAVs Swarms

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Abstract. In this paper, we coordinate the challenging interference problem of UAVs swarms as to maximizing the throughput of networks with Doppler frequency shifts and jamming, a hierarchical framework of group-centric network is considered for manned aerial vehicles operated in time division duplex (TDD) modes. In this case, according to different frequency division duplex (FDD) modes in cluster heads and sub-networks, the approximate methods for cross-tier and co-tier interferences are derived. Furthermore, an interference coordination algorithm is proposed to achieve a better trade-off for the performance of UAVs swarms based on dynamic particle swarm optimization (PSO). Simulation results compared with traditional optimization algorithms, demonstrates the proposed algorithm can improve the overall throughput significantly.

1. Introduction
With high maneuver ability and low cost, unmanned aerial vehicles (UAVs) have been found with a wide range of military and civilian prospects in recent years, such as reconnaissance surveillance, penetration attacks, communication relays, and etc [1-3]. Moreover, it also provides advances for line-of-sight (LOS) communication links on demand with rapid deployment, flexible configuration and reconfiguration in time, as well as the improvement of communication performance. UAVs come in various sizes and large UAVs may be used singly in missions while small ones in formations or swarms. In the future, the UAV Swarms will become an important formation of strike. In all of these applications, the use of UAVs for continuous large-capacity wireless communication is expected to play an important role, and up to date, there are two ways to achieve it.

On the one hand, the promising techniques for mobile communications can improve the bandwidth and throughput of channels, such as Multiple-input multiple-output (MIMO) and full-duplex, which will expand applications for UAVs vastly. MIMO techniques can improve channel capacity by increasing the rate of spatial multiplex, and further reduce the impact on channel fade [4,5]. With the development of 5G technology, the advantages of full-duplex high communication rate and spectrum utilization are gradually highlighted. However, there are few works on the application of UAV swarms in combination with MIMO and full-duplex technology. And on the other, mitigating interference between channels deserves our attention for the throughput. The research on interference mitigation is mainly planed for heterogeneous cellular networks currently, especially coordination in dense scenarios of 5G technologies [6,7]. In order to broaden the coverage of cellular networks, many studies on interference management for UAV-aided cellular networks have been conducted in recent years. Due to the mobility and intelligence level of UAVs as well as the lack of fixed backhaul links.

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and centralized control, it is necessary to centralized control in the loop, and the distributed clustering structures such as group-centric network (GCN) - scalable, efficient, and resilient group communications in a local region will become the main instantiations for UAV networks. To address the needs of UAV networks information sharing requirements, there will be more challenging about serious interference problem restricted to the throughput in networks, especially in densely distributed scenarios such as natural disaster areas or swarm saturation confrontations, which affects the overall operational effectiveness. Thus, effective interference management techniques specifically designed for UAV swarms are needed.

The rest of the paper is organized as follows. Section II describes the system model for swarms framework and full-duplex mode. In Section III, we introduce the FDD downlink transmission scheme for manned aerial vehicles or stations (MAS), and derive an approximation of cross- and inter-tier interferences between MAS and CHVs with the SINR. After that, we propose a centralized interference coordination algorithm based on the derived throughput and dynamic particle swarm optimization. Moreover, the ergodic rate of proportions to different numbers of antennas and CHVs are analyzed. Simulation results are presented in Section IV, and we conclude the paper in Section V.

2. System Models

2.1 Swarms Communication Framework

In this paper, the two-tier clustering framework of group centric network of manned-unmanned aerial vehicles swarms is present as the scenario and the interference coordination problems of the cluster heads in the interconnected groups are mainly considered. Here, the network structure has heterogeneity, self-organization, human-in-the-loop control, and other features. Among them, the manned aerial vehicle or control station (MAS) with MIMO antennas N is responsible for providing wireless communication services for UAV clusters. Although MIMO technology has been extensively implemented in communication systems due to its high spectral efficiency and superior diversity performance, its application for UAV systems is still hindered by several factors of the high signal processing complexity as well as hardware costs and power consumption. In this case, UAVs are equipped with a single antenna in full-duplex modes.

The network is designed as an adaptive hierarchical structure. The first tier is for sub-group intra-communication, and the second is sub-group inter-communication. Moreover, the nodes in the second tier are generated (adaptive election or mandatory assignment) by cluster CHVs S in the first tier. In addition, according to the different mission needs and the characteristics of UAVs, it is divided into reconnaissance subgroups and strike subgroups for swarms. The decentralized reconnaissance subgroups adopt the self-organizing modes for USVs K, which is convenient for sharing intelligence. Due to the complexities of the confrontation environment and the compositions, the hierarchical structure of the cluster heads-cluster members (CHV-CMV) is adopted for the divided s strike subgroups, which is accessible to network management and expansion.

2.2 Full-Duplex Communication Mode

In the whole communication process of UAV swarms, it is considered that the full-duplex technology will bring about different levels of interference coordination problems, especially for intra- and inter-communications between the sub-groups of the swarms in the FDD modes. According to the literatures on full-duplex research, each UAV can operate in different full-duplex modes in the future, which can be broadly categorized into two types: out-of-band full-duplex OBFD (the uplink and downlink are conducted in orthogonal channels) and in-band full-duplex IBFD (the uplink and downlink channels are in the same frequency band). In other words, they may also refer to transmitting and receiving in distinct frequency or co-frequency modes simultaneously.

Because the MAS can communicate wirelessly with the USVs and the CHVs at the same time, different spectrum allocation methods will lead to diverse interference coordination problems in the transmission. Furthermore, we can divide the available frequency band into two parts F1 and F2 by
extension, and assume that the uplink channel of the MAS is $F_1$ and the downlink channel is $F_2$. As such, the selection between $F_1$ and $F_2$ for channel modes will directly determine its full duplex mode corresponding to USVs and CHVs, and which generates different types of co-tier or cross-tier interference, as shown in Figure 1. If a CHV selects $F_1$ as the uplink channel, then the CHV works in OBFD mode, and vice versa. In this case, we refer to the set of swarms working in OBFD modes as $S_O$, and the others working in IBFD mode as $S_I$, where $|S_O|+|S_I|=S$, and $S_O\cap S_I=\emptyset$.

Figure 1. Distribution of interference in different FDD modes.

Since the communications in swarms are centralized and controlled by clustering of MAS, and considering the TDD mode operated by MAS as well as the difference between uplink and downlink channels (the capacity requirement of the downlink channels is much larger than the uplink), the summary of capacities of the downlink channels above is taken as the reference to the network throughput.

3. Interference Coordination

3.1 Interference Function

Due to different mode selections of USVs and CHVs will bring complicated co-tier and cross-tier interference problems, it is necessary to assign modes operated in the swarms in advance for specific tasks. In this section, to maximize the overall throughput of the swarms, the interference coordination problem can be modeled as a specific optimization problem of the 0-1 programming. According to Shannon's theorem, the overall throughput of the swarms can be obtained by

$$C = C_{USV} + C^{O}_{CHV} + C^{I}_{CHV}$$

$$= \sum_{k} B_U \log_2 \left(1 + r_{USV} \right) + \sum_{i} B_C \log_2 \left(1 + r_{CHV}^O \right)$$

$$+ \sum_{i} B_C \log_2 \left(1 + r_{CHV}^I \right)$$

where $C_{USV}$, $C^{O}_{CHV}$ and $C^{I}_{CHV}$ represent the throughput of MAS operated in TDD modes to USV, the throughputs of CHVs operated in OBFD modes and in IBFD modes respectively. Besides, $B_U$ and $B_C$ denote the channel bandwidth for USVs and CHVs. An indicating vector $x = [x_1, x_2, \ldots, x_i, \ldots, x_j]$ is used to select the full duplex mode of CHVs, where $x_i$ is a 0-1 variable constrained by

$$x_i = \begin{cases} 0, & \text{CHV}_i \text{ is operated in OBFD mode} \\ 1, & \text{CHV}_i \text{ is operated in IBFD mode} \end{cases}$$
Therefore, the optimization problem of the overall throughput can be derived as
\[ C = \sum_{k=1}^{K} B_k \log_2 \left( 1 + \frac{r_{CSV}}{s} \right) + \sum_{i=1}^{S} \left( 1 - x_i \right) B_C \log_2 \left( 1 + \frac{r_{CIV}}{s} \right) \]
\[ + \sum_{i=1}^{S} x_i B_C \log_2 \left( 1 + \frac{r_{CIV}}{s} \right) \]
subject to \( x_i \in [0,1], i = 1,2,\ldots,S \) \((3)\)

Obviously, it can be seen that the centralized interference coordination problem is a complex combinatorial optimization problem, and also considering the non-convex characteristics of the feasible domain along with the objective function, the intelligent optimization methods such as particle swarm optimization can be used to solve this problem.

3.2 Centralized Coordination based on Dynamic PSO (DyCenIC)

The particle swarm optimization (PSO) algorithm [8] is newly developed evolutionary technique. Due to the characteristics of efficient search, easy implementation, and quick convergence, nowadays, PSO has gained much attention to diverse issues in different fields, especially for solving multivariable and nonlinear problems.

For the \( N \)-dimensional search space, we assume a mode particle swarm of the number of patterns \( S \) consisting of particles \( x = (x_1, x_2, \ldots, x_N) \), and each mode particle is represented by position information and velocity information. Among them, the \( i \)-th mode particle \( x_i = (x_{i1}, x_{i2}, \ldots, x_{in}) \) is represented as a potential solution—that is, the position in the \( N \)-dimensional search space. According to the objective function, the throughput can be calculated corresponding to each mode particle \( x_i \). Then the speed of the \( i \)-th model particle \( v_i = (v_{i1}, v_{i2}, \ldots, v_{in}) \) is used for the update of weights. The particles are updated as follows:
\[ x_{ik}^{k+1} = x_{ik}^k + v_{ik}^{k+1} \] \((4)\)

According to the size of the throughput currently, the mode particle gradually moves from the initial position to the optimal solution. Moreover, the particles update itself velocity and position to prepare for the next iteration by the individual extremum \( P_i = (p_{i1}, p_{i2}, \ldots, p_{in})^T \) and group extremum \( P_g = (p_{g1}, p_{g2}, \ldots, p_{gn})^T \). The dynamic iteration formula is defined as
\[ v_{ik}^{k+1} = \omega(k) v_{ik}^k + c_1 r_1 (P_{ik} - x_{ik}^k) + c_2 r_2 (P_{gk} - x_{ik}^k), \quad i = 1,2,\ldots,S \] \((5)\)
where \( \omega(k) \) is the dynamic inertia weight, \( \omega(k) = \omega_i - (\omega_i - \omega_e) (K_{max} - k)/K_{max} \). Among them, \( \omega_i \) is the initial weight, and \( \omega_e \) is the weight of the iteration to the maximum, generally \( \omega_i = 0.9, \omega_e = 0.4 \). \( k \) and \( K_{max} \) are the current and the maximum iterations respectively, \( c_1 \) and \( c_2 \) are the acceleration factors, and \( r_1 \) and \( r_2 \) are numbers distributed randomly in the range of \([0, 1]\).

Considering the motion dynamics and time-sensitivity of the swarms, in order to adapt to the dynamic environment and further tracking the dynamic extremum, while avoiding the mode particles falling into the optimization process of the previous environment, we introduce a probe-response mechanism to make the particles of the whole population obtain external ability of perceiving environment change. Furthermore, the mechanism can update the population after detecting changes in the environment to adapt to the dynamic environment. The adaptive environment updating process is obtained as
\[ P_i^{k+1} = \begin{cases} \frac{1}{k} P_i^k, f(X_i^{k+1}) > f(X_i^k) \\ X_i^{k+1}, f(X_i^{k+1}) \leq f(X_i^k) \end{cases} \] \((6)\)
Among them, $p_i$ indicates the individual extremum of the $i$th particle in past records at the $k$th iteration, and $f(x_i)$ is the throughput corresponding to $x_i$. Through updating the environment adaptively, the individual extremum of particle in past records can be gradually left. In the end, it achieves to avoid the particles falling into the previous and have adaptive ability to the dynamic environment.

4. Results & Discussion

The effectiveness of the interference coordination algorithm in this paper is validated through numerical investigation and event-driven simulation on MATLAB®, and different optimization methods (e.g. Genetic Algorithm (GA), Gradient Descent algorithm (GD), Greedy Algorithm (GRA) and traditional PSO Algorithm) are used to solve the interference coordination problem, as well as their respective advantages and disadvantages are analyzed. At the same time, according to the three-dimensional spatial distribution and the technical application characteristics of UAV swarms currently, the considered scenario comprises two types of UAVs moving randomly in the light of a random way-point (RWP) model and a group of them moving also considering RWP mobility models. Meanwhile, the hierarchical sequence is configured by the reconnaissance subgroup-manned vehicles-attack subgroup. For the order of the internal actions of the swarms, we use the existing Follow-Leader rules to organize and refer to the collision-avoid mechanisms.

4.1 MIMO Antennas

Figure 2 reflects the impact of the number of MIMO antennas in MAS on throughput and operating modes selection. It can be found that the increase in the number of MIMO antennas can lead to ascension in throughput, grow and descend cyclically in period as well. The maximum points appear in the numbers of antennas 6, 16 and 26, and then the throughput declines rapidly. This is because of the improper configuration of antennas, as the number of MIMO antennas increases, the self-interference problem that will be introduced into the antenna to deal with, and it is also an important topic for research on large-scale MIMO how to eliminate self-interference between antennas.

![Figure 2. Network capacity versus the number of antennas.](image)

4.2 Full Duplex

Figure 3 compares the DyCenIC algorithm with traditional optimization methods for the optimal throughput of the network and ratio of the selection IBFD mode. It can be found that within a certain range (numbers of sub-network at most 30), the optimal throughput obtained by the network changes almost linearly and rises slowly with the increase of UAVs cluster heads. Moreover, when the numbers of CHVs are within the range of [35 40], the emergent effect of the group becomes prominent. Therefore, increasing the density of the clusters to a certain extent can improve the overall throughput and ensure the implementation of saturation strike for swarms. Beyond a certain range, the internal interference problem is severe due to the dense deployment of the swarms, and it is difficult to
coordinate with each other, which seriously restricts the overall communication capability of the swarms.

![Figure 3](image-url)

**Figure 3.** Network capacity versus the number of CHVs.

### 4.3 Effectiveness

In order to compare the time complexity of the algorithms, Figure 4 shows the running time of various algorithms considered in this paper. The running time of DyCenIC algorithm and PSO algorithm are significantly lower than other algorithms, which amount to half of the GA algorithm. And the running time of GD algorithm is liner with the increase of CHVs almost, whereas it grows sharply when the number of CHVs is above 40. However, the time variety of GRA algorithm changes exponentially with CHVs. Furthermore, with the dense deployment of swarms, the timeliness of the algorithm becomes more and more obvious. The time complexity of the five algorithms listed is $O(S^3)$, yet the DyCenIC algorithm has a faster convergence rate.

![Figure 4](image-url)

**Figure 4.** CPU time of algorithms versus the number of CHVs.

### 5. Conclusion

In this paper, we investigate the problem of inter-tier interference coordination for UAV swarms communication network, where vehicles operate in the time-division duplex and frequency-division duplex modes relatively. In this case, a typical application scenario and framework analysis of a two-tier UAV swarms communication network are proposed, consisting of a MIMO enabled aerial control station and a group of UAV clusters with full-duplex modes in consideration of path loss and Doppler shifts under the aeronautical channel. To suppress the interference and maximize the overall throughput with the influence of jamming, we derive a centralized interference coordination algorithm from achieving a better trade-off for the performance in UAV swarms. It is hoped that the framework and models described in this article will help pave the way for researchers to design and build the communication systems of UAVs-enhanced swarms in the future.
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