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Frequency-aware Trajectory and Power Control for Multi-UAV Systems

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***Abstract*—Deploying large numbers of unmanned aerial vehicles (UAVs) within a region can result in an overcrowded radio frequency (RF) spectrum, requiring UAVs to coordinate frequency selection and mobility to prevent data loss. Current work in interference coordination for multi-UAV systems reduces interference through the use of either trajectory and power control or channel assignments, but not both. We propose a novel controller which selects channels, creates trajectories, and controls transmit power for each UAV to increase the networking capacity of a multi-UAV system. Results show that the proposed controller yields 27% increased network capacity over state of the art UAV frequency reuse algorithms, 152% increased network capacity over state of the art UAV trajectory and power controllers, and 135% faster control overall.**

***Index Terms*—Frequency reuse, Interference coordination, UAVs**

I. Introduction

Unmanned aerial vehicles (UAVs) are versatile for aerial monitoring [1], disaster response [2][3][4], and surveillance applications [5] due to their ability to move between and gather information from multiple points of interest. Quadrotors in particular have fine control over positioning and strong line of sight (LOS) link propagation characteristics. However, LOS links introduce the challenge of interference coordination for UAVs sharing the same channel. For example, consider when multiple UAVs are communicating with ground users in emergency response or surveillance applications. UAVs may communicate over orthogonal channels or compete for a limited number of shared channels, where cross-interference degrades the rate of information transfer.

Previous work in trajectory and power control has tried to solve interference coordination on a single channel [6], but trajectories and powers can often be tuned further given a multi-channel assignment. On the other hand, frequency reuse has been studied for a single band channel assignment given trajectories [7][12], but these trajectories are static and single band channel assignment forces usage of uniform path loss characteristics. Combining the approaches is non-trivial since the resulting problem is non-convex and computationally expensive to solve.

Recent developments in low-power, low-cost, and long-range radios have enabled rapid spectrum sensing [8] and software control over RF inferfaces such as frequency, gains, and bandwidth. These allow us to make systems more frequency-agile, which is useful for overcoming unexpected interference and handling distributed spectrum allocation in dynamic environments. Our proposed controller utilizes this frequency-agility to both avoid channel collisions and assign frequencies from multiple bands, which have differing bandwidth and path loss characteristics. It is important to jointly consider the mobility and connectivity problems, as this leads to better trajectories and interference coordination than approaches which consider them separately.

Contributions. Our proposed frequency-aware trajectory power controller (FTPC) tackles trajectory, power control, and frequency allocation, which have not been previously combined, resulting in a solution that outperforms existing methods while addressing new considerations in channel propagation characteristics and frequency reuse. To manage the complexity, we formulate the problem as an alternating optimization that iteratively solves channel assignment and trajectory-power control out to a time horizon. Channel assignment is a combinatorial problem that assigns frequencies to vehicle-user links to maximize the spatial reuse of frequencies across the region of operation. Trajectory-power control assigns trajectories and transmission powers to each vehicle, and is solved by a successive convex approximation to maximize the overall rate of information transfer. We evaluate the proposed FTPC in simulation against a state-of-the-art trajectory and power controller (TPC) [6] and a graph-coloring frequency reuse algorithm (GCA) [7] on a problem where UAVs are linked to ground users, comparing the sum rate of information transfer. We demonstrate that the proposed controller is able to achieve 27% increased network capacity over GCA [7] and 152% increased network capacity over TPC [6] due to frequency reuse and cross-interference reduction, while speeding up control by 135%.

II. Related Work

Trajectory and power control for UAVs has been implemented with both alternating and joint optimization controllers [9][10][11]. The state-of-the-art work involves a successive convex approximation that maximizes the rate of information transfer between UAVs and ground terminals, which runs faster than similar alternating optimization controllers [6]. Solutions for trajectory and power are computed out to a time horizon in discrete time steps. Our proposed work extends [6]

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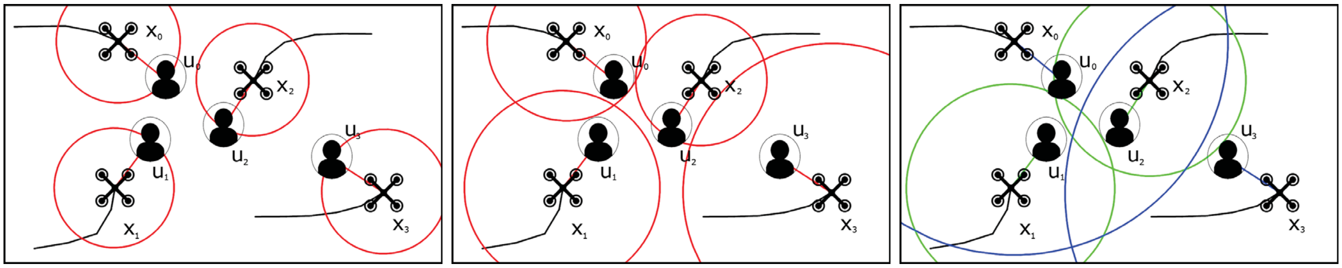


(a) Single channel, uniform power (b) Single channel, varied power (c) Multiple channels, varied power

Fig. 1: Frequency reuse and interference coordination for (a) naive single channel, (b) optimized single channel, and (c) optimized multi-channel configurations. Circle color represents channel frequency for drone-user pair. Larger circle size indicates higher transmit power, which results in increased data rate and higher cross-interference for other pairs on the same channel. Multi-channel communication allows for higher power and higher total data rate.

by adding a channel assignment axis to each UAV followed by solving separate instances of trajectory and power control on each channel, which reduces cross interference and results in better sum rates and faster control as shown in Section IV.

Recent work has explored frequency reuse in settings involving mobility. These utilize game theoretic approaches to find good channel assignments for objectives such as reducing interference or channel switching costs [12][13][14]. The state-of-the-art work solves a graph coloring problem which changes over time due to a set of given trajectories for vehicles [7]. These frequency reuse approaches work best with channels from the same band which have uniform propagation characteristics. To improve upon existing methods, the proposed controller recognizes that different frequencies have different propagation characteristics, which results in improved reuse on higher frequencies. Furthermore, by controlling path and transmission powers alongside frequency selection, the proposed controller is able to achieve higher sum rates and reduce interference further than [7] as shown in Section IV.

III. Problem Formulation

The goal is to control each UAV's transmit power, channel assignment, and trajectory in 3-dimensional space to maximize the rate at which information is transmitted within the system. We define the region $A \subseteq \mathbb{R}^3$ which contains N ground users at given locations $u_i \in A$ paired with N vehicles $x_i \in X$ at locations $q_i \in A$ for an interference coordination situation. Ground users are connected to vehicles through wireless links using frequencies $f_i \in F$ where F can contain frequencies from multiple bands. It is important to not only assign frequencies to each vehicle, but also to include the propagation characteristics of each frequency to maximize frequency reuse and enable higher power transmissions. Received signal and interference power can be calculated as a function of transmit power, link distance, and channel frequency. Fig. 1 illustrates the effect of channel and power assignments on cross-interference, where the circles around each UAV represent the ranges $d_{reuse}(f)$ under which cross-interference is significant on the frequency of the used link.

Assuming a user-vehicle link uses frequency f_i, the received power of a signal p^r_{ij} by a user u_i from a vehicle x_j with transmit power p^t_j at distance d_{ij} can be modeled using free-space path loss (FSPL) as shown in Eq. (1) [15]. FSPL is appropriate because, as demonstrated in previous studies [16], aerial vehicles typically operate in open space environments with sufficient altitude such that there are very few obstructions if any between vehicles. At heights of above 100 meters, the effects of multipath fading degrade enough and the setup approaches more ideal line of sight conditions that a path loss exponent of 2 is reasonable.

$$p^r_{ij} = p^t_j + 20\,log_{10}\left(\frac{c}{4\pi d_{ij}\, f_i}\right) \tag{1}$$

The maximum theoretical rate of data transfer that can be achieved on a link is the channel capacity, which can be modeled using the Shannon-Hartley theorem [17]. Assuming line of sight between a user-vehicle pair with a user u_i and vehicle x_i, the channel capacity C_i of a link using frequency f_i given the power of a signal at the receiver p^r_{ii}, bandwidth B, and power of noise n is shown in Eq. (2):

$$C_i = B \cdot log_2\left(1 + \frac{p^r_{ii}}{n}\right) \tag{2}$$

For a single user-vehicle pair, the noise power n is the variance of interfering additive white Gaussian noise. For situations where multiple user-vehicle pairs are reusing frequency bands, we must consider cross-interference, where the communication of one user-vehicle pair will act as additional interference for the communication link of another user-vehicle pair. The channel capacity including cross-interference terms can be calculated as shown in Eq. (3):

$$C_i = B \cdot log_2\left(1 + \frac{p^r_{ii}}{\sigma^2 + \sum_{i \neq j} I^f_{ij}\, p^r_{ji}}\right) \tag{3}$$

where p^r_{ji} is the received power between vehicle x_j and user u_i, σ^2 is the variance of interfering additive white Gaussian noise, and the last term in the denominator is cross-interference from other nearby links on the same frequency. Cross-interference is calculated using an indicator function I^f_{ij}, which evaluates to 1 if the frequencies f_i and f_j are the same and 0 otherwise, and d_{ij}, as the distance between the transmitting vehicle x_i and receiving user u_j. The distance d_{ij} is calculated using the L2-norm $||q_i - u_j||_2$, where q_i represents the position of UAV i.

The benefit of mobile vehicles is that they can move to improve their channel capacity. Frequencies, trajectories, and transmit powers are defined over a given time horizon for T discrete intervals, which models the battery life of an aerial vehicle. The problem is defined as choosing frequencies $f_i[t]$, trajectories $q_i[t]$, and transmit powers $p_i^t[t]$ for every UAV x_i such that the UAVs achieve the highest total throughput possible for a set of user-UAV pairs. The objective function is to maximize the aggregate sum rate of information transfer over the time period $0 \leq t \leq T$. This translates to better link capacities between UAVs and users, which can be expressed mathematically as follows:

$$\begin{aligned} \underset{f_i[t], p_i^t[t], q_i[t]}{\text{argmax}} \quad & \sum_{t=1}^{T} \sum_{i=1}^{N} C_i[t] \\ \text{subject to} \quad & q_i[t] \in A \quad f_i[t] \in F \\ & ||q_i[t] - q_i[t-1]||_2 \leq v_{max} \\ & 0 \leq p_i^t[t] \leq P_{max} \\ & \text{Eq. (1), (3)} \\ & \forall \ i \in N, t \in T \end{aligned} \tag{4}$$

Here, $C_i[t]$ is calculated using the capacity from Eq. (3) as evaluated at a time point t, which can be expressed in terms of $f_i[t]$, $p_i[t]$, and $q_i[t]$ by substituting for appropriate variables. The movement of the aerial vehicle is limited such that the distance between any two consecutive points cannot exceed a maximum velocity constraint v_{max}. This problem is difficult to solve optimally since the trajectories and powers depend on channel assignments, while channel assignments depend on trajectories and powers. The channel assignment problem alone is combinatorial, so as the size of the problem increases, it becomes critical to rely on heuristic algorithms for choosing frequencies, trajectories, and powers.

A. Proposed Controller

The proposed controller starts with an initial trajectory and power assignment initialization where vehicles move directly towards the associated ground users at maximum speed v_{max} and gradually increase their transmission power as they get close. This initial set of trajectories and powers is usually a feasible solution to the trajectory power controller successive convex approximation and speeds up convergence by ending in a configuration where each UAV hovers as close as possible to their associated user. This maximizes the instantaneous sum rate of information transfer for each link and is typically very close to the optimal hovering locations. This is also defined over a time horizon such that the controller can take user movements and changes in the radio frequency spectrum into account in the next time period. The proposed controller then applies an alternating optimization with the following two steps until the channel assignment stops changing.

- Obtain a channel assignment given trajectories and powers using an adaptive band graph coloring algorithm. The trajectories and transmission powers impact the frequency selection due to cross-interference from inter-vehicle and vehicle-user proximity.
- Obtain trajectories and transmission power given a channel assignment by performing a joint trajectory and power optimization for each channel via successive convex approximation.

The resulting set of channel assignments, trajectories, and powers at the end of the second step is used in evaluation of cost. Convergence occurs when the channel assignment remains the same between two iterations, as the same channel assignment results in the same set of trajectories and powers. Furthermore, convergence is guaranteed since both steps reduce the overall cost of the objective function, and will eventually reach a point where it is unable to do so. The next subsections outline the proposed channel assignment algorithm and trajectory power optimizations.

B. Adaptive Band Channel Assignment

Frequencies from different bands (e.g. 2.4 and 5 GHz) have different propagation characteristics, and therefore different optimal frequency reuse spacings. Since signal degredation is proportional to f_i^2 and d_{ii}^2, more UAVs can be assigned higher frequency channels at shorter separation distances with comparable interference levels to those on lower frequency channels at longer distance.

The goal of the proposed controller is to assign a channel to each UAV from the given set of frequencies $F = \{f_1, f_2, ...f_N\}$ that both maximizes frequency reuse and balances a minimum tolerable signal-to-interference-noise ratio for each frequency dependent on the distance between potentially interfering vehicles. We perform channel assignment with a novel adaptive band graph coloring algorithm, which is the first graph coloring algorithm that takes propagation characteristics of multiple bands into account. This balances reuse of higher frequencies with utilization of lower frequencies. The channel assignment takes into account the current trajectory and power constraints for each vehicle to adjust the parameters of the graph coloring appropriately, resulting in channel assignments for each vehicle using the method outlined in Algorithm 1.

First, we calculate an initial interference power threshold p_{thr} using free-space path loss in Eq. (5), which specifies an upper bound on allowed interference between any two UAVs separated by distance d on the same channel f. The minimum reuse distance for each frequency channel d_{reuse} represents the minimum allowed separation between two transmitters that share a channel and is calculated using Eq. (6). While d_{reuse} may differ by channel, UAVs on any channel never receive an interference signal with power higher than p_{thr} provided they maintain a separation of at least d_{reuse}.

$$p_{thr} = p^t - L = P_{max} + 20 \log_{10}\left(\frac{c}{4\pi df}\right) \tag{5}$$

$$d_{reuse}(f) = \frac{p_{thr}}{f^2} \tag{6}$$

A graph can then be constructed for each frequency f using the current trajectory endpoints as vertices V connected by edges E for endpoints that are within distance $d_{reuse}(f)$ as shown in Eq. (7) and (8). Edge endpoints cannot both be assigned the frequency in consideration as doing so would violate the minimum separation constraint given p_{thr}.

$$V_f = q_i[T] \; \forall \; i \tag{7}$$

$$E_f = (q_i[T], q_j[T]) \; \forall \; i, j, ||q_i[T], q_j[T]|| < d_{reuse}(f) \tag{8}$$

The proposed controller then attempts to assign as many vehicles to the channel with highest reuse frequency as possible using the graph and a connected component subroutine to prevent adjacent vertices from being assigned the same channel. This process is repeated with the unassigned UAVs on the next highest reuse frequency, and so on until either all vehicles are assigned a channel or there are no channels remaining. In the case that at least one vehicle is not assigned a channel, a search with a lower p_{thr} is required, which decreases the reuse distance for every channel and therefore leads to a lower amount of edges in G for every frequency.

For any configuration, there is guaranteed to be a finite p^*_{thr} where p^*_{thr} is the largest p_{thr} that produces a valid channel assignment for every UAV. This is a desirable value for p_{thr} since this is the point where the interference level is as low as possible and every UAV is assigned a channel. The approach used in the controller is to start p_{thr} at a high value (much higher than a potential p^*_{thr}) with an exponential decay on p_{thr} in the event of a failed channel assignment, multiplying it by a factor of 0.99 at each failed iteration to relax the allowed interference slightly. The strategy of decaying p_{thr} in the event of a failed assignment will always eventually reach a point where $p_{thr} \leq p^*_{thr}$, which guarantees a channel assignment for every UAV. Locking in the channel assignments at the point where p_{thr} crosses p^*_{thr} then minimizes interference and maximizes frequency reuse. Assigning channels given a single p_{thr} is implemented in Algorithm 1, and this process is repeated each time p_{thr} is updated until a valid channel assignment is found.

C. Trajectory and Power Control

The other objective of the proposed controller is trajectory and power control given a channel assignment, which can be solved for using a successive convex approximation. Without loss of generality, the problem can be decomposed into smaller instances of the trajectory and control problem on each channel. The general approach for solving a single instance of the trajectory and power control (TPC) problem can be applied from [6], which implements joint trajectory and power control assuming all vehicles share a single channel with uniform propagation characteristics. The proposed controller leverages previous work, specifically Equations 19-23 and Algorithm 1 from [6] to maximize sum rate of information transfer throughout time period T for each instance of the TPC problem on each channel.

The lower bound of the rate function and optimization objective can be found in [6], which states that it is locally tight and concave in $p_k[t]$ and $q_k[t]$. The addition of frequency to the interference term and change in rate objective calculation do not impact the concavity of the function, so it maintains the same properties for optimization as described in [6].

Algorithm 1: Channel Assignment

```
Input: p_i[t], q_i[t], F, p_thr
Output: f_i[t]
Sort F for iteration in descending order
for f ∈ F do
    Construct graph G(V, E) as in Eq. (7), 8
    V excludes vehicles with assigned frequencies
    Find all connected components cc in G using
      visiting and flagging
    for cc ∈ G do
        while size(cc) > 0 do
            Find vertex u with lowest degree in cc
            f_u[t] = f ∀ 0 ≤ t ≤ T
            for v ∈ neighbors(u) do
                G.remove(v)
            end
            Remove u from consideration on all F
        end
    end
end
```

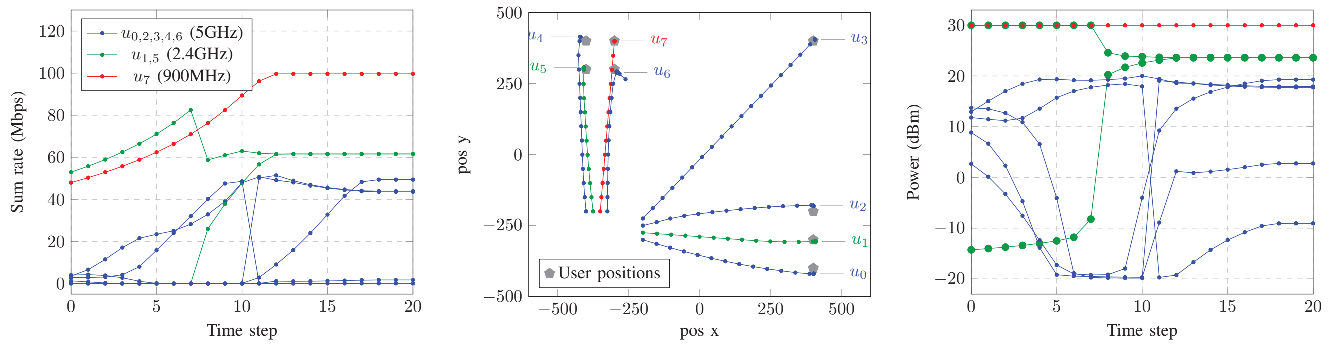
By maximizing the lower bounds on sum rates for each frequency, a set of trajectories and powers for every UAV is generated to maximize the sum rate objective given a channel assignment. Furthermore, decomposing the problem into subproblems speeds up computation of the successive convex approximation algorithm, as the number of constraints between UAVs is exponential in the problem size.

IV. Results

In our evaluation of the proposed frequency-aware trajectory power controller (FTPC), we deploy vehicles in a simulated environment to communicate with a set of users and optimize for the maximum sum rate of information transfer over time period T. We compare the proposed controller against instances of fixed channel joint trajectory and transmit power controllers [6] as well as channel assignment algorithms with fixed trajectories and powers such as FDMA and the channel assignments similar to [7] with fixed trajectories and powers to demonstrate how the proposed controller achieves higher aggregate link capacity through both better frequency reuse and interference reduction.

TABLE I: Simulation Parameters for FTPC Case Study and Comparisons

Parameter	Description	Value
P_{max}	Max power	30 dBm
N_0	Noise floor	-90 dBm
A	Region bounds	[-500 m, 500 m] for x, y [0 m, 100 m] for z
h_{min}	Min UAV height	100 m
F	Freq channels	[915 MHz, 2.4 GHz, 5.2 GHz]
B	Bandwidth	10 MHz



(a) Sum rate over time for each UAV shows convergence as UAVs approach final hover positions (b) Traj. of each UAV curve to best avoid interference and end on points slightly offset from users (c) Transmit Power over time for each UAV shows power changing as UAVs move adjust power

Fig. 2: Proposed FTPC implementation on case study (8 UAVs, 3 channels, 30 time steps), where color represents UAV freq

For all experiments, we refer to Table I for configuration of default simulation parameters. Channels were selected from ISM bands with the center frequency of each channel used in calculation of loss characteristics. Since 30 dBm is the maximum legal transmit power for 5 GHz bands in several countries, we set it as the maximum power. In the following simulation scenarios, we set the time horizon to 30 time steps. Any remaining time after the vehicles reach a stable state is used to send data at the highest rates possible, encouraging fast convergence of all control variables to their final states.

A. FTPC Case Study

When running FTPC in an instance with 8 UAVs and 3 channels on different bands (5.2 GHz, 2.4 GHz, 915 MHz) in a 1 km^2 region, we demonstrate on a small case how channel assignments, trajectories, and powers all work together to produce an improved sum rate. In the scenario shown in Fig. 2b, four users are placed in a tight square at the top left of the region, one user is placed at the top right, and three are placed at the bottom right. Each UAV is colored by selected frequency, with blue, green, and red corresponding to 5.2 GHz, 2.4 GHz, and 915 MHz respectively. All UAVs take off at the bottom left of the region, with trajectories that end close to the associated users.

The proposed channel assignment recognized that the tightly clustered set of users in the square need to be assigned to different channels, and utilized the lower frequencies available in 915 MHz and 2.4 GHz to do so. We also see that in the bottom right cluster of users, the middle link is dropped to 2.4GHz to best reuse frequencies and reduce interference in the cluster. 915 MHz would have been a poorer choice here since it would interfere more heavily with the other 915 MHz UAV than with the 2.4 GHz UAV due to the spacing of the users. In Fig. 2a, we see how each vehicle contributes to the overall sum rate. The UAV on 915 MHz experienced no cross-interference and the two on 2.4 GHz experienced a low degree of cross-interference, so they contributed greatly to the total sum rate compared to the UAVs on 5.2 GHz. As shown in Fig. 2b, the trajectories of vehicles which share channels end in hovering positions slightly offset from their associated users due to the effects of cross interference, while the vehicles on lower frequencies are able to hover more closely to the associated users. Varying distances to users for different UAVs sharing a channel can also affect the trajectory as seen in the square of users in the top left, where one UAV arrives slightly earlier, but is displaced a bit when the second UAV arrives and starts increasing its transmission power. The UAVs sharing the 5.2 GHz channel had to coordinate their transmit powers as they traveled towards the hovering positions, shown in Fig. 2c. While the UAV experiencing no cross interference on the 915 MHz channel was able to transmit on full power at all times, the combination of mobility and cross-interference for UAVs on the 2.4 and 5.2 GHz channels caused the transmit powers of each UAV to change throughout the time it took for the UAVs to reach their hovering positions.

TABLE II: Sum rate comparisons for proposed and competing implementations on case study

Implementation	Data Transferred (GB)	Relative Performance
Fixed freq [6]	2.74	1.00x
FDMA [6]	3.48	1.27x
Fixed trajectory	6.90	2.52x
Proposed FTPC	**8.77**	**3.20x**

B. FTPC Comparison to the State of the Art

As shown in the sum rates achieved by each implementation on the case study in Table II, FTPC's usage of trajectory and power control given a channel assignment lead to higher sum rates than competing approaches. Relative performance is scaled in relation to the amount of data transferred by the state of the art work with fixed channel assignments [6].

Overall, the fixed frequency trajectory power controller from [6] has the lowest total rate over the mission as seen in Table II with only 2.74 GB total of data transmitted due to the high interference incurred when UAVs share the same channel. The FDMA channel assignment with the trajectory power controller from [6] is an improvement over this, but still underperforms compared to controllers with higher frequency reuse. Using a fixed trajectory with the proposed graph coloring approach spreads channel allocations throughout the region, reducing interference beyond pure trajectory and power con-

TABLE III: Channel assignments for uniformly distributed UAVs

64 UAVs, 6 freqs		16 UAVs, 5 freqs	
Freq (GHz)	Num. UAVs	Freq (GHz)	Num. UAVs
5.22	33	5.22	8
5.20	18	5.20	3
5.18	8	5.18	3
2.437	3	2.412	1
2.412	1	0.915	1
0.915	1		

trol. However, the full proposed FTPC controller achieves 8.77 GB transmitted due to its ability to tune both the trajectories and powers in response to channel assignments as well as the channel assignments in response to trajectories and powers. This is a 27% improvement over the fixed trajectory controller, and a 152% improvement over the state of the art trajectory power controller [6] with FDMA channel assignments.

The proposed FTPC controller also speeds up trajectory and power control relative to [6] by decomposing the problem into smaller instances on each frequency. Since the number of constraints is exponential in problem size, solving multiple subproblems of smaller size for each frequency channel runs faster than a large, single channel optimization problem. For example, in this case the proposed FTPC controller had a largest subproblem size of 5 compared to 8 in the trajectory power controller [6], leading to 135% faster control.

C. *Frequency Reuse*

When compared to a trajectory and power controller with fixed channel assignments [6] in the case study, it is clear that the ability to coordinate frequency selection in FTPC leads to a significant increase in the sum rate. Assigning all vehicles to a single band, such as in a TDMA or FDMA scheme, negatively impacts the transmission rate of each vehicle due to a reduction in sub-band bandwidth for each additional UAV. In comparison with the proposed controller (FTPC), an FDMA scheme has no cross-interference which enables full-power transmissions, but allocates lower bandwidth per UAV. Although these two schemes both fully utilize the available radio frequency spectrum at each time step, the proposed controller with adaptive band channel assignment has much higher frequency reuse and takes into consideration the spacing and mobility of the UAVs at each time step, leading to higher sum rates as shown in Table II.

In different scenarios with 16 UAVs uniformly distributed throughout a region on 5 channels and 64 UAVs on 6 channels, FTPC produces channel assignments as shown in Table III. As seen there, FTPC appropriately allocates more UAVs to the frequencies with higher reuse characteristics, while still taking advantage of lower frequencies which can be assigned fewer UAVs at similar interference levels.

V. Conclusion

We proposed a frequency-aware trajectory-power controller (FTPC) for multi-UAV systems to solve a joint frequency, trajectory, and power control problem. We split the problem into channel assignment and trajectory-power control subproblems and solved them using alternating optimization. Although both are still NP-hard problems, channel assignment is solved through a novel adaptive band graph-coloring frequency reuse algorithm while trajectory-power control is solved by utilizing successive convex approximation techniques. In simulation, the proposed method resulted in 27% increased channel capacity, 135% faster control, increased frequency reuse, and increased interference reduction compared to controllers which only use a subset of FTPC's control variables.

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