# On Provision of Resilient Connectivity in Cognitive Unmanned Aerial Vehicles

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***Abstract*—Mobile ad-hoc network (MANET) can be established in the areas/scenarios where the infrastructure networks are either out of service or no more available. MANETs have a lot of applications in sensor networks. Generally, a MANET deploys mobile ground nodes to set up a network. However, there can be some severe scenarios such as flood, battlefield, rescue operations, etc. where these ground nodes cannot be deployed. In such cases, a network of unmanned aerial vehicles (UAVs) can be a more viable option. Normally, UAVs operates on IEEE L-Band, IEEE S-Band or ISM band. These bands are already overcrowded, therefore, UAVs will face the problem of the spectrum scarcity. To resolve this issue cognitive radio (CR) is a most promising technology. Hence, in this work, we focus on CR based UAVs. As CR is based on opportunistic spectrum access, therefore, it is quite possible that all UAVs do not have one single channel available to communicate with each other. They need to form clusters for their communication depending on the availability of the channel. However, channel availability is intermittent because of opportunistic spectrum access. This may result in reforming of the cluster again and again. To avoid this frequent re-clustering and to maintain connectivity among the UAVs, in this paper, we present a resilient clustering technique with a concept of introducing a backup channel for each cluster. Simulation results show the significance of the proposed technique.**

## I. INTRODUCTION

Flying ad-hoc networks (FANETs) are networks with nodes often called unmanned aerial vehicles (UAVs) have many applications which do not require a human operator or human intervention is risky. For example, military operations, traffic surveillance and monitoring and other rescue operations [1]. These UAVs have to operate in a significantly larger geographical area. Thus, a single UAV may not be enough to complete the desired task and we may require a multi-UAV system. Each UAV in this system is equipped with a number of sensors as well as processing, communication, and power units. The type of the sensors a UAV is equipped with depends on the task it is meant for. Also, UAVs can differ in their sizes and the altitude at which they fly depending on the needs of a particular application [2].

To perform various tasks, these UAVs have to exchange information among them. For that one of the biggest challenges is to establish connectivity among these UAVs. Normally, UAVs operate on IEEE S-Band, IEEE L-Band, and ISM Band [3]. Generally, UAVs coexist with a number of other wireless devices, which may be using technologies such as WiFi and Zigbee etc. which are also operating on these aforementioned bands. This may lead to the fact that UAVs face spectrum scarcity for their communication due to increased utilization of these spectrum bands. To address this problem, cognitive radio (CR) is a promising technology offering dynamic spectrum access. Thus, these UAVs need to be armed with CR technology so that other than the aforementioned unlicensed bands, the UAVs can also access the licensed spectrum in an opportunistic manner without interfering with the licensed users (also named as PUs) [4]. Several efforts have been reported regarding the application of CR technology in various field, to name a few, wireless sensor network [4], wireless mesh network [5], Internet of things [6], and cellular networks [7]. Hence, in this work, we focus on connecting the UAVs with the help of CR technology.

Equipping UAVs with CR technology for provisioning of connectivity among them poses certain challenges. First of all, UAVs are accessing the licensed channel based on their availability, which may lead to a condition that a channel may be available to one UAV may not be available to other UAVs. Two UAVs can communicate only on a channel if this channel is available to both of them at the same time. To address this problem, we present a cluster based mechanism in which different UAVs form a cluster based on some common channel among them so that coordination among them happens via this common channel. Second, since UAVs are the secondary users of the licensed spectrum they have to vacate the channel which they are using whenever a PU returns back over that channel. Suppose a cluster is formed over a common channel among UAVs and a PU comes back to that channel, this may disconnect all the UAVs which are coordinating with each other using this channel and to recover the connectivity, this requires reclustering among UAVs. To address this problem, we introduce the concept of the backup channel in which the clusters are formed with two channels in common between UAVs. Out of these two channels, one is serving as the main channel and other as the backup, in this way, the frequent clustering can be avoided. The main contribution of this paper is as follows:

- A methodology to integrate CR technology in multi-UAV systems is presented.
- A clustering mechanism is introduced for provisioning of connectivity among CR based multi-UAVs.
- A concept of the backup channel to provide a resilient clustering among multi-UAVs by avoiding the need for doing frequent re-clustering.

The remaining paper is organized as follows. Section II describes the problem statement and the nomenclature of the presented work. Section III discuss the related work for CR based UAV communication. The proposed work is explained and discussed in section IV. Section V presents the simulation results and section VI concludes the paper.

## II. Problem Statement and Nomenclature

Mostly multi-UAV systems have groups of UAVs for different tasks. To accomplish these tasks UAVs within the group need to coordinate with each other. For that, a common channel is a better choice for coordination among UAVs. However, having this coordination over unlicensed spectrum band may not be a good solution as the number of devices using these bands are increasing day by day. Therefore, these UAVs have to operate opportunistically on the licensed spectrum using CR technology. However, the biggest challenge in this type of connectivity is that, since UAVs have to access the channels opportunistically, a single channel might not be available to all the UAVs in a group. Also, two UAVs even within the transmission range of each other cannot communicate with each other if there is no common channel among them. To resolve this issue, clustering can be done on the basis of common channels among the UAVs. Each cluster of UAVs is assigned some particular channel which is common among all the UAVs of that cluster. However, another problem arises is that the assigned channel may become unavailable after some time and again the connectivity among UAVs is disturbed, which may result in reforming the clustering once again. Therefore, some solution needs to be provided that can avoid this frequent re-clustering among the UAVs. In order to do this, we propose a technique of introducing the concept of the backup channel. Instead of making a cluster based on a single channel, each cluster is designed in such a way that there are two common channels among the UAVs. One of these channels is the primary channel and the other is the backup channel. In this way, the frequency of redoing clustering again and again can be reduced by compromising on the number of clusters, i.e., by this technique cluster size may be reduced which results in more number of clusters. The nomenclature of the paper is given as in Table I.

TABLE I: Symbols and their Description.

| **Notions** | **Description** |
|---|---|
| $T$ | Number of channels in the network. |
| $C_i$ | List of empty channels available at ith UAV. |
| $N_i$ | neighbors of the ith UAVs |
| $S_1$ | Bipartite graph vertices including ith UAV and its Neighbor UAVs. |
| $M$ | Number of Elements in $S_1$ |
| $S_2$ | Bipartite graph Vertices including $C_i$. |
| $G_i(S_1, S_2, E)$ | Bipartite graph for ith UAV. |
| $X_i$ | UAVs in maximum edge biclique graph of UAV. |
| $Y_i$ | Channel in maximum edge biclique graph of UAV. |
| $Q(X_i, Y_i)$ | Maximum-edge biclique graph for the ith UAV. |
| $w_i$ | Weight for the ith UAV i.e. product of $X_i$ and $Y_i$. |
| $\rho$ | PU arrival Rate |
| $F$ | Number of elements in $X_i$ |
| $K$ | Number of elements in $Y_i$ |

## III. Related Work

The efforts done related to the connectivity in UAV network can be broadly categorized into two types, i.e., air to ground communication and air to air communication. Since this work is focused on CR based UAV network. Therefore, in this section, we briefly discuss work related to the earlier mentioned subject. A comprehensive survey about the integration of CRs into UAVs network, its benefits, applications, and challenges are presented in [8]. Another similar survey work is presented in [9], but this surveys with an extending scope for the use of CR in all types of aeronautical applications. In [10] a survey is conducted regarding only air to air communication (means only among UAVs). In [11], authors first presented motivation behind the use of CR for UAVs. Then, a spectrum sensing architecture to enable UAVs communication over the unlicensed spectrum is proposed. In [12], the various anticipated challenges and issues related to connectivity and robustness for future UAVs communication are discussed. In [13], authors presented an energy detection based spectrum sensing scheme for broadband communication of a UAVs network. In [14], authors established a framework to improve the connectivity between a UAV and a ground station while controlling the trajectory as well as the power of transmission of that UAV. According to the best of our knowledge, this is the first work of its kind as far as UAVs communication is concerned. In this work, we focus on air to air communication and try to establish robust connectivity among CR based UAVs.

## IV. PROPOSED TECHNIQUE

The main goal of the proposed technique is to group UAVs into clusters such that a large number of idle channels are common among the UAVs of that cluster. The advantage of this type of clustering is that UAVs have more options in terms of selecting a channel for their coordination. Moreover, in case a PU has occupied the channel in which UAVs coordination is in progress, then, UAVs can shift their ongoing coordination again and again.

### A. Cluster Formation Procedure

Following the discovery of the neighboring UAVs and exchanging the list of the number of available channels $C$, each UAV$_i$ becomes aware of its all neighbors, denoted $N_i$, and the set of available channels $C_j$ with them, where UAV$_j \in N_i$. Based on this, the rest of the method to form the cluster of UAVs includes following steps:

- Each UAV$_i$ broadcasts its list of available channels $C_i$.
- Each UAV$_i$ constructs a bipartite graph $G(S_1, S_2, E)$ based on its neighbors $N_i$, channel available at this UAV $C_i$ and the channel available at its neighboring UAVs i.e., $C_j$.
- Each UAV$_i$ extracts a maximum edge biclique graph $Q(X_i, Y_i)$ that will be explained later. Given the chosen graph $Q(X_i, Y_i)$, the product of the number of UAVs $X_i$ and channels $Y_i$ represents the weight $w_i$ of the UAV$_i$.
- Each UAV$_i$ send this computed $w_i$, along with $X_i$, and $Y_i$ to all of its neighboring UAVs.
- Each UAV compares its weight with its neighboring UAVs, if the weight of ith UAV is greater than its neighbors that is $w_i > w_j, \forall$ UAV$_j \in N_i$, then, UAV$_i$ declares itself as cluster head, otherwise it has to join as a cluster member with the UAV having the highest weight among its neighbors.

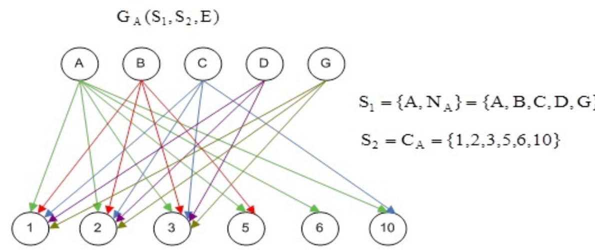


Fig. 1: A bipartite graph.

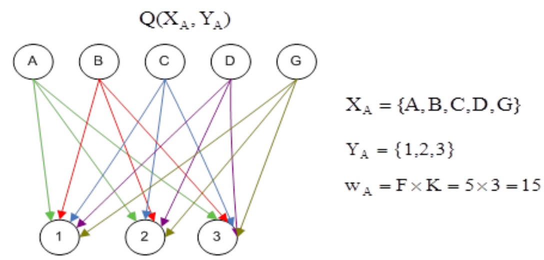


Fig. 2: A maximum edge bipartite graph.

### B. Construction of Maximum Edge Bipartite Graph

After the exchange of the information among the neighboring UAVs, a bipartite graph can be formed. A bipartite graph is a graph $G(V, E)$ with vertices V that can be divided into two disjoint sets $S_1$ and $S_2$ such that an edge $E$ always connects a vertex in $S_1$ to a vertex in $S_2$. For our problem, a bipartite graph $G(S_1, S_2, E)$ is constructed for each UAV$_i$, where the set $S_1$ includes UAV$_i$ and its neighboring UAVs $N_i$ and the set $S_2$ includes the available channels $C_i$. An edge $(x, y)$ exists between UAVs and channel such that $x \in S_1$ and $y \in S_2$, i.e., $x$ is in the list of UAV$_i$ or its neighbors and $y$ is in list channel available to that UAV and also present in the channel list of UAV$_i$. Fig. 1 shows an example of a bipartite graph constructed for a UAV named as UAV$_A$.

A bipartite graph is termed biclique graph $Q(V = X \cup Y, E)$ if for each $x \in X$ and $y$, there exists an edge between $x$ and $y$. In this study, we are interested in a maximum edge biclique graph that has the maximum product of cluster size (depends on the number of UAVs in a cluster) and the set of channels common among these UAVs. An example of the maximum-edge biclique graph for UAV$_A$ is shown in Fig. 2.

### *C. Algorithm to extract maximum biclique graph.*

**Algorithm 1** Extract maximum edge biclique graph from a bipartite graph.

**Input :** $G(S_1, S_2, E)$
**Output :** $Q(X_i, Y_i)$
$Y_i \leftarrow C_i$
**for** `j=1 to M` **do**
  **Find** `k where` $UAV_k \in S_1$ `such that` $R = Y_i \cap C_k$
  **if** $R = \phi$ **then**
    **break**
  **else**
    $I_i[j] = k$
    $S_1 \leftarrow S_1 - UAV_k$
    $X_i \leftarrow X_i \cap UAV_k$
    $Y_i \leftarrow Y_i \cap C_k$
    $P_i[j] = F \times K$
  **end if**
**end for**
**Find** $j^* = argmax_j P_i[j]$
**Return** $w_i = P_i[j]$
**Return** $Q(X_i, Y_i)$

The algorithm to extract maximum edge biclique graph from a bipartite graph is presented in Algorithm 1. This algorithm is performed for all UAVs, which result in a biclique graph for each UAV in the network. Finally, the maximum biclique graph Q with the highest product of the number of UAVs and the number of common control channels is eventually obtained. The result is a set of nodes $X_i$ and the set of channels which are common $Y_i$. $Y_i$ is obtained by taking the intersection of channels available to every element of $X_i$. The UAVs having the same biclique graph form a cluster with the cluster head having the highest weight among all other UAVs and $Y_i$ is the set of common channels for this cluster of UAVs.

## V. SIMULATION RESULTS

To evaluate the performance of the proposed technique, we carried out simulations in MATLAB. We consider two variants of the proposed technique. In the first variant, named as “Technique 1”, there is no limit on the number of common channels in a cluster among UAVs. In the second variant, named as “Technique 2”, there is limit posed on the common channels that if the number of common channels is 2, just try to maximize the number of UAVs in a cluster; however, still it is possible that the final cluster has more than 2 common channels. The performance metrics taken into account is the average number of formed clusters and the average number of channels which are common in each cluster. The performance metrics are examined by variation in the number of UAVs and primary licensed users (PUs) arrival rate in the simulation. Let us assume that of $T = 30$ be the total number of channels available to be assigned to the clusters. Moreover, it is also supposed that each UAV can communicate with other UAV which is within a radio transmission range of this UAV and it is taken to be $x = 40m$. Also, the total area over which this CR network of UAVs is established is taken to be $100 \times 100m^2$. The whole area is considered to be in the form of a grid of one hundred equal elements. Both UAVs and PUs are randomly distributed in the region. Any two UAVs lying in the same or adjacent grid elements have at least 70 percent of the available channels common to each other. The PU arrival rate is denoted as $\rho$ that indicates how often a channel is occupied by a PU. The value of $\rho$ can vary from 0 to 1, however, we took it 0.1 unless otherwise specified. All these parameters setting are shown in Table II.

TABLE II: Simulation Parameters.

| Parameters | Values |
|---|---|
| Area $(A)$ | $100 \times 100$ $m^2$ |
| Number of UAVs $(N)$ | $100 \sim 1000$ |
| Number of Channels $(T)$ | 100 |
| Transmission Range $(x)$ | 40 m |
| PU Arrival Rate $(\rho)$ | $0 \sim 1$ |

Fig. 3 shows the average number of cluster form with the variations in UAVs. The number of UAVs is varied from 100 to 1000 while the PU arrival rate is fixed to 0.1. When the number of UAVs is small, more clusters are formed because the UAVs may be away from each other. On the other hand, when the number of UAVs is increased, the average number of clusters starts decreasing because each UAV may find other UAVs within its transmission range. Moreover, it can also be seen from the result the average number of clusters starts saturating after a certain number of UAVs becomes the part of the network. Furthermore, it can also be seen that the number of clusters formed in “Technique 2” is less than the number of clusters formed in “Technique 1”. This is because “Technique 2” tries to increase the cluster size by trying to restrict the number of common channels up to 2, which ultimately results in the formation of less number of clusters.

Fig. 4 shows the average number of common channels in each cluster versus the number of UAVs. The number of UAVs is varied from 100 to 1000 and the PU arrival rate is fixed to 0.1. When the number of UAVs is small, the number of common

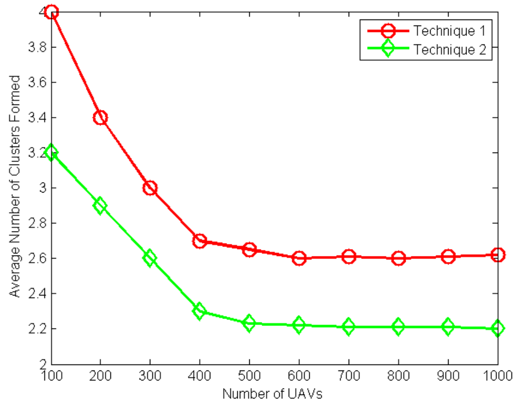


Fig. 3: Average clusters formed versus numbers of UAVs.

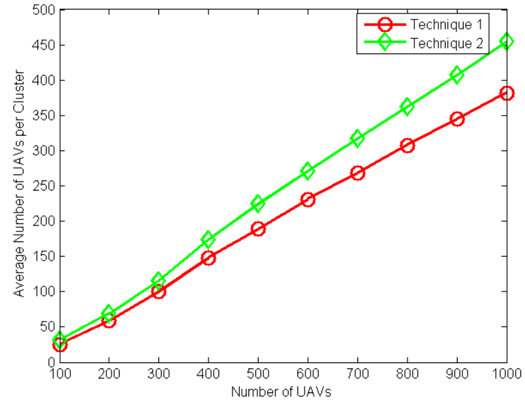


Fig. 5: Average numbers of UAVs per clusters.

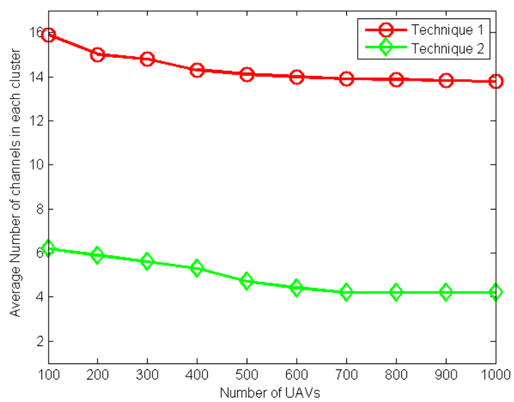


Fig. 4: Average number of channels per cluster versus numbers of UAVs.

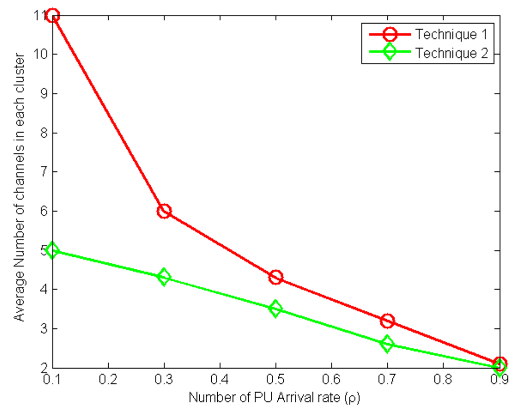


Fig. 6: Average number of channels per cluster versus PU arrival rate.

channels in each formed cluster is more; however, with the increased number of UAVs, the number of channels is reduced. Because with more UAVs, the probability of finding the same channel with more and more UAVs is reduced. Moreover, it can also be seen that number of common channels in each cluster in "Technique 2" is much less than in "Technique 1", because "Technique 2" tries to restrict the number of common channels equal to 2, however, it can exceed once cluster is formed as shown in Fig. 4.

Fig. 5 shows the average number of UAVs per cluster versus the variation in the number of UAVs. The number of UAVs is varied from 100 to 1000 while the PU arrival rate is kept the same as 0.1. the result shows that as the number of UAVs increased the number of UAVs per cluster also increased. However, the number of UAVs per cluster is higher in "Technique 2" as compared to "Technique 1". This is because we are trying to maximize the product of UAVs and the number of common channels in "Technique 2" is set to 2, therefore, clusters are formed with more number of UAVs. This shows the trade-off that if we want to form a bigger cluster we should move towards less number of common channels among the UAVs within a cluster.

Fig. 6 shows the average number of channels in each cluster versus the PU arrival rate. The number of UAVs is fixed to 1000, while the PU arrival rate is varied from 0.1 to 0.9. The result shows that with more PU arrival rate the number of channels common for each cluster gets decreased. This is mainly because with more PU arrival rate less number of channels will be available to UAVs, hence each cluster formed will also be assigned less number of channels.

## VI. CONCLUSION

In this paper, we examined the connectivity establishment problem in CR network based multi-UAV system. More specifically, we looked at the effect of spectrum heterogeneity among UAVs and PU activity impact in the formation of a cluster for connectivity among UAVs. To avoid frequent re-clustering, our technique provides more backup channels to each cluster. Whenever a channel gets occupied by a PU, instead of re-clustering, control information exchange migrates from the occupied channel to one of the other backup channels. Our proposed scheme shows result in terms of an average number of channels in a cluster with a varying number of UAVs and PU activity. Our work can be enhanced further to extend the connectivity among the clusters in the future.

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