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Cognitive Communication Scheme for Unmanned Aerial Vehicle Operation

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Abstract— **An intelligent and agile wireless communication scheme is a key factor in provision of efficient air-to-ground (A2G) communication for unmanned aerial vehicles (UAVs) operations. For this purpose we review and propose an architecture for aeronautical cognitive communication system (ACCS) that will be providing command, control and communication (C3) link between ground control stations (GCSs) and multiple UAVs utilizing cognitive radio (CR) concept. The factors reviewed and accounted for in the design process are the topology of cognitive detectors, connectivity between cognitive detector and control agency, connection with unmanned traffic management (UTM) system, data link requirements imposed by cognitive scheme, failure notification and recovery, etc. The proposed ACCS is suitable for supporting UAV operations and features a distributed non-communication architecture consisting of GCS network in the ground zone, hybrid data link with the static uplink and the flexible downlink, demonstrating a dynamic nature overall with the frequency handoff scheme generated periodically in accordance with current spectrum environment.**

I. INTRODUCTION

It is widely anticipated that the static spectrum allocation will not be sufficient for providing reliable communication for unmanned aerial vehicles (UAVs) in the multitude of their emerging applications, especially those of higher criticality, such as search and rescue, surveillance, inspection, etc. Development of adaptive and agile communication scheme then becomes necessary for improving communication efficiency for provision of the reliable command, control and communications (C3) link with UAVs. According to review [1] due to high dynamics of UAVs and limited spectrum resources, wireless air-to-ground (A2G) C3 communication link presents more challenges in comparison with other links, such as terrestrial communication and control and non-payload communication (CNPC). Considering these challenges general requirements for UAV communication system have been formulated in [2]:

- High availability for sense and avoid applications in terms of the communication system downtime and continuity.
- An integrated coverage of UAV missions with both networked or non-networked controllers.
- Preemption design for priority control of multiple UAVs.
- Support of communication between UAVs and ground stations via other UAVs.
- Compatibility with data links for manned aircrafts.

Many of these requirements are still not addressed even at the system level, which drives the need of proposing an advanced communication system to bridge these gaps by reviewing and integrating available technologies.

Since the cognitive radio (CR) was proposed in [3], it is considered as a promising technology to improve communication efficiency through maximization of spectrum resources utilization. The cognitive communication system allows CR-enabled users to share the same frequency or channel. In this system two types of users are categorized according to presence of license for communication channel: licensed primary users (PUs) and unlicensed secondary users (SUs). In CR definition, SUs can access channel (frequency) opportunistically when PUs of this channel are idle, providing that SUs do not cause any interference to PUs.

Numerous studies have been done on cognitive technology, covering spectrum awareness and sensing [4], spectrum sharing [5], spectrum handoff [6] and dynamic spectrum access (DSA) [7], but few of these studies are considering scenarios of UAV A2G communication. Lack of the coverage in the literature drives the need of review and design of high-level architecture of aeronautical cognitive communication system (ACCS).

II. COGNITIVE FUNCTIONALITY OF AERONAUTICAL COGNITIVE COMMUNICATION SYSTEM

In contrast to conventional communication system, utilizing static schemes, lacking adaptation to RF environment the proposed ACCS concept generates communication solutions based on real-time spectrum sensing outcomes that are dynamic and flexible, i.e. they are adapting to spectrum environment. Two additional (cognitive) functions are particularly emphasized in the proposed ACCS: spectrum awareness and dynamic spectrum access (DSA). The ACCS component providing the spectrum awareness functionality is called cognitive detector (CD) and control agency (CA) the component responsible for allocation of spectrum resources. CA plays main role in allocating spectrum resources and in coordinating with other agents in this process. Below we summarize considerations in the ACCS design related to CDs and CAs.

A. *Cognitive Detector and Control Agency*

A cognitive detector (CD) is a component capable of sensing a radio frequency (RF) environment, recognizing transmissions, parameters or spectrum opportunities and interfacing with CA autonomously. An alternative to obtaining the information on RF environment is to obtain a radio

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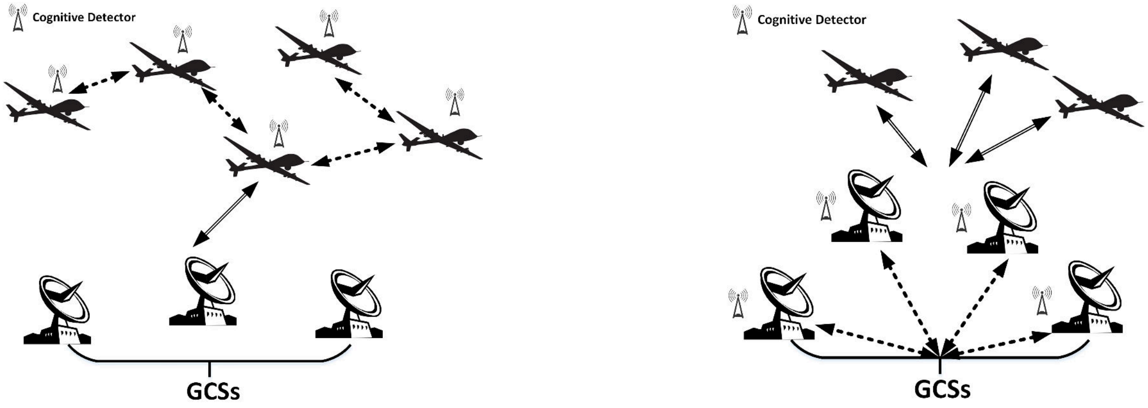


(a) ACCS based on CD-FANETs

(b) ACCS based on CD-INETs

Fig. 1. Two types of aeronautical cognitive communication networks

environment maps (REMs) externally, e.g. from other agents forming collaborative spectrum sensing scheme. Another classification of the CD is based on the presence of capability to estimate PUs' traffic model. In this classification, two types of detectors: reactive detector and proactive detector, are commonly defined [8].

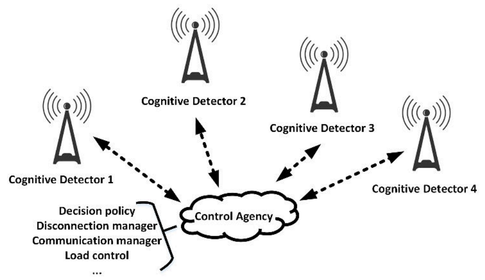
Information on identified by CDs spectrum resources is then utilized by control agency (CA) that allows management of spectrum resources as well as establishing coordination with other components in ACCS. Some high level functions provided by CA are the decision making, disconnection management, communication management, load control, etc.

B. CD-based Communication Networks

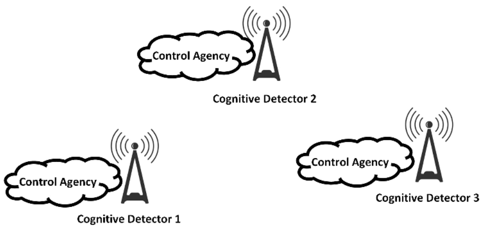
Cognitive functionality of the ACCS requires appropriate support from the communication network. There are two main communication networks supporting air-to-ground connectivity: flying ad hoc networks (FANETs or AANETs) [9] and infrastructural networks (INETS) [10]. FANETs establish connection between GCSs and UAVs indirectly via several UAV-to-UAV or UAV-to-GCS data links, while INETs form direct connection between UAVs and GCSs. Accordingly, two types of networks utilizing CDs can be defined: airborne, forming cognitive detector based flying ad hoc networks (CD-FANETs) shown in Fig. 1(a) and ground based, forming cognitive detector based infrastructural networks (CD-INETs), shown in Fig. 1(b).

CD-FANETs implies, in contrast to FANETs, that UAVs are equipped with CDs to enable awareness of surrounding RF environment, and thus to form an aerial communication network for communication with other UAVs and ground stations using flexible communication schemes. The main challenge in implementation of these networks is related to high mobility and dynamism of UAVs' network topology that make it difficult to enable stable connectivity, e.g. by using mesh network of UAVs [11] or modify MAC layer to improve link establishment [12]. Another issue is in large computation demands of cognitive sensing algorithms that make the implementation of CD-based networks extremely challenging in case of the small platforms severely limited in both load bearing and power capacity.

As infrastructure-based networks are well established and widely used in mobile ad hoc networks (MANETs) already [13], they are considered to be promising for ACCS as they can be adapted easily to serve air-to-infrastructure links [14]. Some studies on infrastructure-enabled communication for UAV-related scenarios have been done [10], [15], [16]. In contrast to CD-FANETs, size, weight, power and cost (SWaP-C) requirements in CD-INETs are lower as the computations for spectrum detection are shifted from airborne platform to GCSs, making it more practical in implementation. However, CD-INETs also brings new challenges, for instance how to upload DSA schemes from GCS to UAVs, what data should be included in the DSA transmission, and how to maintain the quality of service (QoS) by having such architecture.

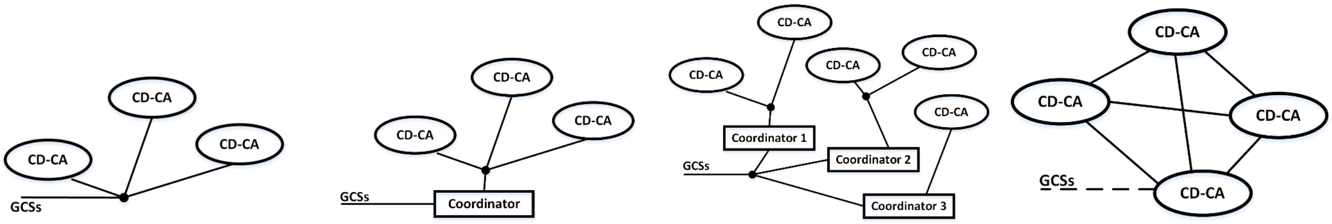


(a) Centralized CD-INET



(b) Distributed CD-INET

Fig. 2. Network topology of CDs and CAs on the example of CD-INET



(a) Non-communication (b) Master-worker (c) Partially connected (d) Fully connected

Fig. 3. Classification of the distributed network architectures based on communication type

C. Connectivity Between Cognitive Detector and Control Agency

Considering the connectivity within the network of CAs and CDs, two main architectures can be defined: centralized and distributed, presented in Fig. 2(a) and Fig. 2(b) respectively.

1) Centralized Network Architecture: The connectivity using centralized architecture is popular in practice due to its convenient implementation. The centralized architecture in this case means that a group of CDs is linked to one CA directly. Such way of connection forces CA to behave as a master (also called ground central controller in [17]) and together with CDs serving as slaves to form a hierarchical master-slave model. However, when number of slaves (CDs in this case) increases the centralized topology has a risk of reaching a physical limit of handling data, resulting in QoS degradation in terms of data rates, latency, and reliability [18].

2) Distributed Network Architecture: The concept of distributed system is characterized by presence of capability for each agent to make decisions either dependent on nearest neighbours or by itself, i.e. independently. In this case, each CD is required to be combined with a CA, forming CD-CA combination, to enable ability of making decisions. The comparison between centralized and distributed architectures has been reviewed for multiple application areas, e.g. for smart grids [18], in optimization theory [19], etc. Commonly accepted primary advantages of the distributed architecture are the flexibility, scalability, asynchronous operation and reliability.

Considering physical connections in the distributed architecture it can be divided into two types: non-communication and communication-based, where the latter can be further subdivided into master-worker, partially connected and fully connected architectures described in more details below.

Non-communication (also called local or autonomous in [20]) distributed architecture (see Fig. 3(a)) means that CD-CA utilizes its local information only without having connection with other CD-CAs. As a consequence, such type doesn't require the information exchange between CD-CAs, although the connection to a higher level system components is still needed.

The communication-based type means that each CD-CA has collaboration with other CD-CAs partially or globally to make decisions through an intermediate component called coordinator. The diagrams describing these architectures are shown in Fig. 3(b) - Fig. 3(d).

In the master-worker type (see Fig. 3(b)), the information exchange is achieved via a central coordinator, where the coordinator only collects messages and allocates them to the related CD-CA without processing the data. The coordinator is also providing an interface with higher level systems to provide functionality such as monitoring and analyzing health data of the network. Similar to the centralized architecture, master-worker based distributed architecture is also characterized by limited capacity, restricted scalability, presence of unique point of failure and lack of robustness [21], introduced by physical connections.

Partially connected (also called decentralized in [20]) architecture (see Fig. 3(c)) is characterized by presence of groups of CD-CAs that are forming subsystems with own central coordinator. Those subsystems can exchange information through multiple coordinators and form a hybrid multilevel system. When one CD-CA requests data from another subsystems' CD-CA, the communication routing not only covers the internal data flow within the subsystem but also includes the link between coordinators in different subsystems. Compared with master-worker network type, featuring central coordinator, partially connected network reduces communication load on a single coordinator by increasing number of coordinators. This inevitably brings additional challenges in routing / path planning between subsystems, clustering of CD-CAs, network management, etc.

An ideal concept of a distributed system would be achieved if every component is treated equally so the system becomes physically homogeneous. To achieve this a fully connected system (see Fig. 3(d)) commonly utilized in sensor networks [22], [23] is taken into consideration here. Fully connected system is usually characterized by pairwise connections between all CD-CAs so they can share information and collaborate directly. Each CD-CA is considered to be omniscient in this case. This global connectivity in the fully connected architecture results in high throughput requirement of the communication link that is growing quickly with number of CD-CA, difficulties in designing task scheduling mechanism without coordinators, high deployment cost and time, increased communication latency caused by limited throughput.

Apart of the above fundamental distributed network ar-

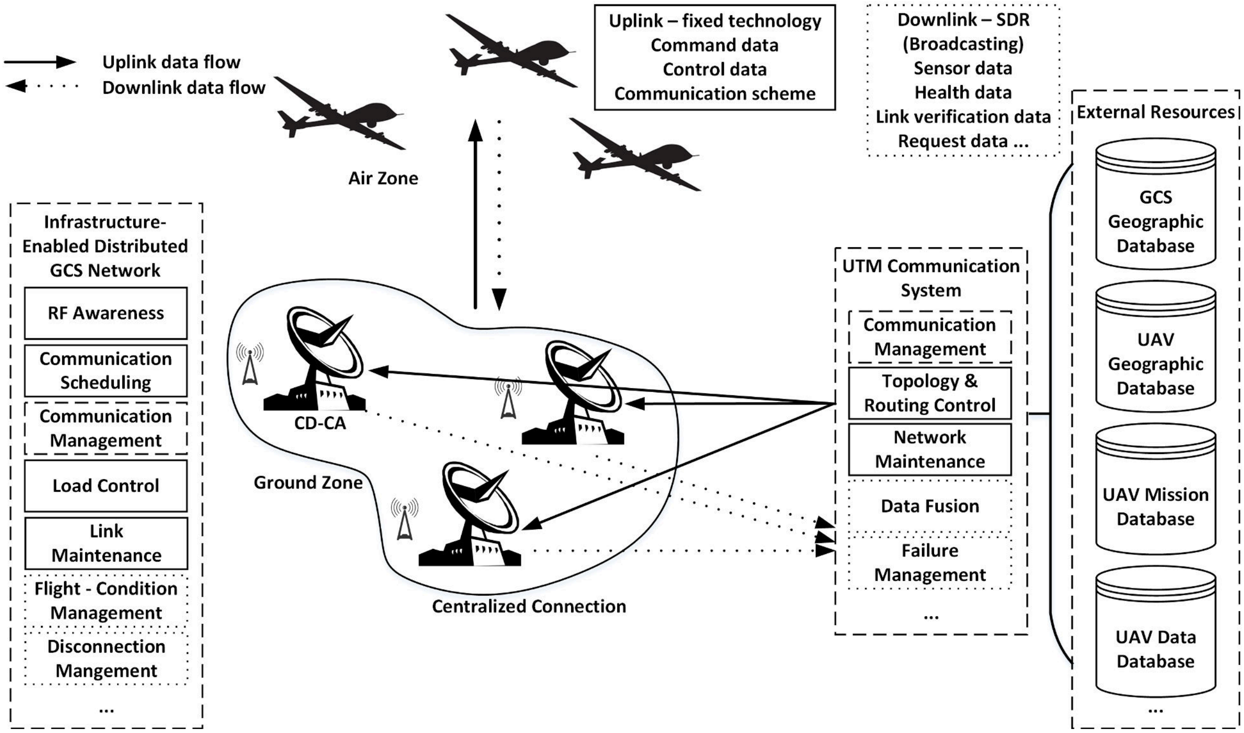


Fig. 4. System architecture of aeronautical cognitive communication system

chitectures, there are other hierarchical or hybrid distributed systems proposed in different areas, where some of the coordinators can control other coordinators. The examples of such architectures are a two-level hierarchical architecture in [24], three-level hierarchical architecture in [25], randomly generated hierarchical architecture in [26]. In this paper, we assume that the CD component is capable of autonomous operation without relying on its neighbours, thus non-communication architecture is able to reduce system complexity.

III. AERONAUTICAL COGNITIVE COMMUNICATION SYSTEM

A. Internal Structure

Based on the functionality considerations, connectivity and deployment framework illustrated in Sec. III-D, we consider five layers, i.e. physical layer (PHY), data link layer, network layer, transport layer and application layer, in open systems interconnection (OSI) model for a further design of ACCS.

The hardware solution in cognitive communication system, both transmitter and receiver are usually utilizing software defined radio (SDR) technology that allows to tackle effectively challenges in parameters configuration in the presence of high variability in RF environment. SDR is also providing the necessary functionality for forming CDs that enable dynamic adjustment of communication parameters, such as frequency, modulation type, type of signal waveform, etc., maintaining quality of service (QoS) or quality of experience (QoE). SDR also supports effective cross-layer design to optimize communication efficiency and implementation of dynamic handoff between different modulation schemes or communication technologies, for instance global system for mobile communications (GSM), orthogonal frequency division multiplexing (OFDM), minimum shift keying (MSK), phase shift keying (PSK), continuous wave (CW), Wi-Fi, 3G/4G/5G, 802.11 b/g, chirp, etc [27]. CR enabled spectrum hopping technology between various frequency bands, such as high frequency (HF), very high frequency (VHF), L-band, S-band, Ku-band, and Ka-band [1], etc., is also achievable with SDR solutions.

Command, control and communication (C3) technology is adopted for constructing ACCS as data link layer providing its validation in UAV operations [28]. Two types of links are defined in a C3 system in terms of data flow direction: uplink and downlink, where the uplink refers to a link for uploading command and control messages from GCS to UAVs and downlink refers to transmission of feedbacks from UAVs to GCS. Uplink is required to have a higher stability and reliability for preventing loss of control in UAV applications, while requirements to downlink are usually formulated in terms of capacity, QoS, delay tolerance, etc.

The transport layer design is completed by implementing some subsystems, such as communication scheduling / management in UTM and GCS as well as link maintenance in GCS. The network layer is formed by introducing subsystems of network maintenance and topology & routing control in UTM.

Based on above remarks, we propose to utilize a hybrid datalink in ACCS: static uplink and flexible downlink scheme. The advantage of such scheme is in improved control reliability and higher throughput in data communication. The proposed ACCS architecture utilizing such hybrid datalink together with non-communication distributed CD-INETs is presented in Fig. 4. In this figure the solid lines represent uplink-related data flow and the dashed lines represent downlink-related data flow. The unmanned traffic management (UTM) system is shown as a high-level system to highlight interaction with general applications of supporting and monitoring UAV operations. ACCS components are split between air zone and ground zone, where the ground zone contains CD enabled infrastructure presented by distributed network of GCSs as well as UTM system components and the air zone includes UAVs using SDR technology enabling flexible transmissions from airborne operators.

B. UTM Communication System

In this section we describe the UTM functions relevant to ACCS implementation that are shown as individual subsystems in UTM communication system in Fig. 4.

Communication management subsystem takes charge of exchanging messages between GCS network, external resources and users. Such point-to-point network layer usually utilizes UDP/TCP protocol combined with IPv4/IPv6 as was presented in [29].

Topology and routing control subsystem is responsible for establishing an optimal topology according to current operational conditions in the ground zone. It generates optimal data flow path in the network to support advanced network protocols, like mesh protocol or self-organized network protocols, so that to satisfy communication requirements, such as minimization of number of node between UTM and GCS, minimization of communication power, reducing delay, etc.

Network maintenance subsystem is diagnosing the operation status of ground zone networks to prevent the system operation failure caused by the nodes.

Data fusion subsystem is responsible for combining messages from different GCSs, removing redundant data and identifying missing pieces of data in cases of receiving redundant messages by multiple GCSs.

The failure management subsystem is responsible for making decisions concerning recovery of the lost connection between GCSs and UAVs as well as reporting loss-of-connection and broadcasting notifications to other systems.

C. External Resources

In order to implement our proposed ACCS, four external databases are necessary in the UTM system to meet minimum operation requirements of ACCS: GCS geographic database, UAV geographic database, UAV mission database and feedback database.

GCS geographic database stores 3-dimensional coordinates of every GCS as well as its operation status, e.g. availability of spectrum, communication capabilities, number of users connected to GCS, etc.

UAV geographic database records and updates location of each UAV in real-time, where the location information can be acquired directly via monitoring equipment like radar or received from UAVs directly, for instance, using automatic dependent surveillance-broadcast (ADS-B) messages.

Similar to operations in civil aviation, UAV mission database registers flight plans for each operation, including operation number, ID of UAV, start time, end time, destination, start location, operation type, estimated flight path, speed, altitude, etc.

The feedback database saves information broadcasted from UAVs through the downlink. The data can be presented by sensor data (e.g. messages, images, video, etc.), health data (e.g. remaining power, mechanical / electrical failure, etc.) or other kinds of requested data. This database functions also as an interface with other components, such as the UTM management system, service providers or service users.

The utilization of external databases: GCS geographic database, UAV geographic database and UAV mission database, is required for generating routing plans in the ground zone network of GCS to upload command and control (C2) messages from the UTM to the corresponding GCS. The feedback database is responsible for data collection and failure management, which were explained above.

D. Ground Control Station Network

Designed as a CD-INET distributed network, the network of GCSs presumes that each GCS is equipped with one CD-CA so it can operate cognitively and autonomously. In order to serve as intermediate transceivers for communication between GCS network and UAVs, a number of subsystems has to be present in each GCS as shown in Fig. 4.

RF awareness subsystem is based on CD and provides basic functionality of spectrum sensing, with detection and prediction algorithms to perform idle frequency or channel detection and identification of spectrum opportunities in the spectral environment.

Following the RF sensing outcomes, the flexible downlink scheme is then generated in the communication scheduling subsystem using frequency handoff algorithms, e.g. the one described in [8], aiming at maximizing spectrum utilization. The generated downlink scheme is designed to be time-triggered, meaning that airborne and ground systems are assumed to be synchronized with time-labeled information included in the MAC layer, e.g. start time and end time of transmission, transmission frequencies, modulation type, communication technology, etc.

The communication management subsystem in GCS network is performing similar functions as the one in the UTM system aiming at exchanging information between the UTM and UAVs. Additional functions of this subsystem in GCS network include transmission C2 messages to UAVs via a static link, monitoring and tracking UAV signals, extracting data from the receivers, and control of the transmission power.

Load control subsystem balances spectrum utilization across frequencies or channels of interest in order to prevent overloading of a single spectrum band creating a risk of QoS reduction for potential users. It also contributes to improvement of the link quality by selecting the spectrum with relatively low occupation.

Link maintenance subsystem ensures the required level of downlink QoS to provide sufficient and reliable delivery of the messages in a complicated environment, where aeronautical ad hoc network (AANET) [9] is particularly involved.

Flight-condition management is critical to provide communication in mobile and highly dynamic conditions of UAV operation scenarios that may result in complicated propagation effects, like Doppler effect, multi-path effect, fading effect, etc. Additional challenges may arise due to some non-typical flight condition, e.g. low remaining power, abnormal altitude, etc.; this subsystem is also expected to deal with them. When failures occur, the flight-condition management subsystem sends warning messages to the failure management subsystem in the UTM and then waits for further commands while attempting to modify communication configurations automatically to recover from the failures.

The disconnection management subsystem tracks UAV signals and monitors status of A2G link by using spectrum sweeping, scanning or wideband sensing technologies. When GCS cannot discover UAV signals within its coverage area, a loss-of-connection message will be sent to the UTM data fusion subsystem to find whether any other GCSs have received the missing messages or not.

E. Air Zone

The communication among UAVs in air zone is not considered in this case, as several technologies have been studied to form self-organizing networks like FANET [10]. As mentioned before, UAVs utilize SDR technology to receive command and control data via a static uplink from GCS network and transmit feedback data with a flexible downlink scheme generated by communication scheduling subsystem in GCS. The transmission of the feedback information such as sensor data, health data, or other request data (those have been explained in Sec. III-C) can be achieved in this case without having an access to a licensed channel, i.e. as a SU. The feedback data can also contain link verification data utilized in link maintenance subsystem as explained in Sec. III-D to support link quality measurement.

IV. CONCLUSION

This paper reviews and integrates CR-enabled subsystems for design of a dynamic air-to-ground communication system, resulting in the proposition of the architecture of the aeronautical cognitive communication system (ACCS) suitable for supporting UAV operations. Within a high-level conceptual design of ACCS, we highlighted common architectures of ground control system infrastructure and discussed an interaction between cognitive detectors CDs and control agencies CAs, resulting in the adoption of non-communication based distributed system architecture to form the ground station networks. A hybrid datalink solution was designed to provide C3 services with a static uplink and flexible (CR-enabled) downlink scheme. A detailed discussion of ACCS system architecture has been performed with consideration of required external resources (databases), network maintenance, failure management, redundancy resolution, link maintenance, etc.

Some of the challenges, e.g. identification and track of UAV signals with a high-speed wideband cognitive detector, generating handoff scheme with scalable resources, etc. are still present in this architecture and are subjects of future work.

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