Requirements, Challenges and Analysis of Alternatives for Wireless Datalinks for Unmanned Aircraft Systems

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***Abstract*—Two key challenges in the design of datalinks for unmanned aircraft (UAS) systems compared to other wireless links are the long range of distances and speeds that need to be covered. The 960 - 1164 MHz part of the IEEE L band has been identified as a candidate spectrum for future manned and unmanned aircraft datalinks. The amount of spectrum available in the L-Band is not sufficient to support video applications common in UASs and so dual-band designs using both L-Band and C-Band are being considered. For L-Band, two projects funded by EUROCONTROL L-Band Digital Aeronautical Communications Systems 1 and 2 (L-DACS1 and L-DACS2) are often mentioned for use in UAS also. We briefly discuss issues with their use for UAS. We compare the two proposals in terms of their scalability, spectral efficiency, and interference resistance. Then we discuss several issues in UAS datalink design including availability, networking, preemption, and chaining. We also propose ways to mitigate interference with other systems in the L-Band.**

***Index Terms*—Unmanned aerial vehicles; Wireless communication; Wireless networks; Radio spectrum management; Aerospace and electronic systems; Communication networks; Communication systems; Data communication; Digital communication; Radio communication**

I. Introduction

NEW datalinks need to be developed for Unmanned Aircraft Systems (UAS) and for commercial manned systems particularly because they will share the same non-segregated air space and would need to be aware of each other's presence.

The key challenges in the design of aeronautical communication systems are the large distances that they need to cover and the high-speed of aircraft. These along with the limited availability of radio frequency spectrum affect the performance of the datalink.

Over the past several years, EUROCONTROL has funded two projects for developing new datalinks for aeronautical communications [1], [2], [3]. These projects resulted in two proposals named L-DACS1 and L-DACS2 are often mentioned in UAS discussions [4]-[9]. It is, therefore, important to analyze their performance. In addition, UAS communication has additional requirements on availability, networking, and traffic management.

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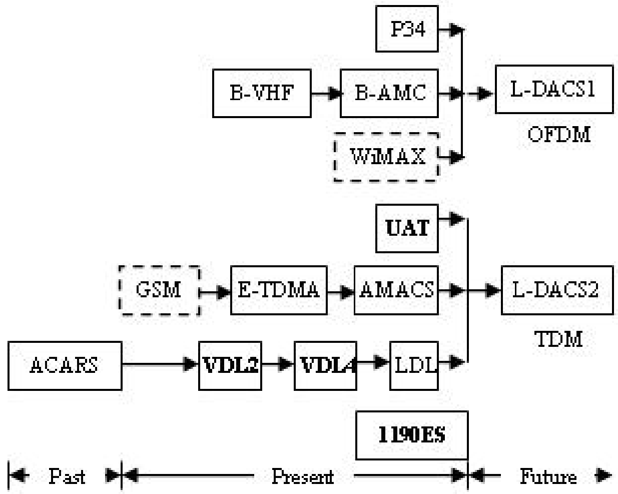

Fig. 1. Evolution of aeronautical datalinks

Even if L-DACS1 or L-DACS2 are not adopted for UAS wireless datalinks, their analysis as presented here is helpful in understanding the issues involved in the design of such links.

This paper is organized as follows. In Section II, we present the evolution of past aeronautical datalinks followed by a discussion of challenges faced in designing aeronautical datalinks in Section III. Section IV discusses suitability of L-DACS1 and L-DACS2 for the next generation of aeronautical communications. In Section V, we present some additional requirements for UAS datalink design. Section VI presents some strategies for mitigation of interference in L-Band. Finally, we summarize our conclusions in Section VII.

II. Evolution of Aeronautical Wireless Datalinks

In order to understand the features and design decisions for future aircraft datalinks, it is helpful to understand the past evolution of these datalinks. This is shown in Fig. 1.

The very first aeronautical data communications system is ACARS (Aircraft Communications Addressing and Reporting). It was developed in 1978 by ARINC Inc. It was widely deployed by ARINC since it was the sole provider of communication services to the entire aeronautical industry. ACARS operated in HF, VHF and SATCOM bands and used analog radio with amplitude modulation for data link services. In 1990s, efforts were made to transition to digital radio and the resulting technologies were called VHF digital link

(VDL). Four versions (or modes) of VDL were developed sequentially called VDL1, VDL2, through VDL4. Of these VDL1 and VDL3 were designed but not deployed. VDL2 will be required in all aircraft in Europe by 2015 and will, therefore, be widely implemented. The FAA (Federal Aviation Administration) NextGen (Next Generation Air Transportation System) program also plans for deployment of VDL2 in the United States. VDL2 allows only aircraft-to-ground communication, while VDL4 added support for aircraft-to-aircraft communication but has seen very limited deployment. Since the VHF band was getting congested, L-Band versions of VDL2 and VDL4 have also been proposed and are known as LDL2 and LDL4, respectively. Again, these have not seen any deployments yet.

In 1998, Hughes Network Systems designed E-TDMA (Extended Time Division Multiple Access) datalink [26] as an extension of popular cellular technology called GSM (Global System for Mobile communication). The key feature of this technology was the introduction of multiple QoS classes using dedicated and on-demand slots. Each aircraft has a dedicated slot in the time region marked as QoS0. The aircraft can use this slot to make requests for other slots in QoS1 and subsequent regions. We mention this here because this technique was subsequently used in AMACS (All purpose Multichannel Aviation Communications System) [24] which was proposed in 2007 and in L-DACS2. AMACS uses time division duplexing (TDD) and divides the frame in two uplink (ground to aircraft) regions and two downlink (aircraft to ground) regions. The first uplink region is used for data transmission while the second uplink region is used for acks and grants. The first downlink region contains one dedicated slot for each aircraft. Again, these slots are used by the aircraft to make requests for data slot allocations in the second downlink region. There is also an insertion region, which is reserved for contention access by new aircraft wanting to join the network.

UAT (Universal Access Transceiver) operates at 978 MHz and provides a burst rate of 1 Mbps using a 3-MHz channel. It is also a TDMA system. Developed in 2002, it allows each aircraft to send one 18 byte or 34 byte ADS-B message per second.

All of the above technologies use what we call "Single-carrier" modulation and time division multiple access (TDMA). For the past 15 years, wireless networks in other (non-aeronautical) communications have moved off to multi-carrier modulations.

The first aeronautical datalink to use multi-carrier modulation was B-VHF (Broadband Very High Frequency) proposal funded by European 6th Framework (FP6) program [25]. It was designed for 118-137 MHz VHF band using MC-CDMA (multi-carrier code division multiple access) and time division duplexing (TDD). In MC-CDMA, each bit is encoded as a sequence of chips (code bits) and then code-bits are used to modulate subcarriers of OFDM (orthogonal frequency division multiplexing). The subcarrier spacing was 2 kHz.

Since VHF band was congested, B-VHF was updated to operate in L-Band and the resulting design was called B-AMC (Broadband Aeronautical Multi-Carrier system). The CDMA was dropped leaving only OFDM. The subcarrier spacing was increased to 10 kHz (to account for increased Doppler spread at higher frequency). To get a reasonable capacity, the required band was increased to two channels of 500 kHz (50 subcarriers 10 kHz apart). The two channels are used for frequency division duplexing (FDD).

Another relevant wireless standard is P34 (Project 34) developed by EIA (Electronic Industry Association) and TIA (Telecommunications Industry Association) for public safety radio. It covers 187.5 km sectors and uses 50, 100, 150 kHz channels in the L-band and uses OFDM.

III. Aeronautical Datalinks: Challenges

Designing aeronautical wireless datalinks (manned or unmanned) is much more challenging than other wireless links. The key challenges are: Long Distance, High-Speed, and Spectrum. In this section we review these challenges. Much of this discussion applies to both UAS and commercial manned civil aviation.

A. Long Distances

The main challenge for aeronautical datalinks is the long distances covered by these datalinks. The most common wireless link used today is IEEE 802.11 links also called WiFi. It covers only 100 meters. IEEE has also developed IEEE 802.16 wireless networks for metropolitan area coverage. This link popularly known as WiMAX uses cell sizes of 1 km in urban areas and 3 km in suburban areas. These sizes also apply to 3GPP LTE [30]. For longer distances, the signal strength decreases rapidly by 2nd to 4th power of the distance. Compare these to aeronautical datalinks that have to cover up to 200 nautical miles, i.e., 360 km. This is two orders of magnitude larger than WiMAX and also cellular networks. This distance results in significant power attenuation in the path and results in a very low spectral efficiency. The efficiency is measured by bits per second per Hertz (bps/Hz). WiMAX networks have an efficiency of 3-5 bps/Hz at 0.9 km [27]. Achieving even 2 bps/Hz is a challenge on aeronautical datalinks.

The long distance also results in large round-trip delays that require large guard times. It takes approximately 1.2 ms for light to travel 360 km one-way. Compare this to just 17 μs required for 5 km in WiMAX networks. The increased guard times further decrease the spectral efficiency.

B. High Speeds

The second challenge is the speed of mobility. WiFi supports very limited mobility. Since the coverage is only a few hundred meters, a car travelling at 100 km/h will need to change base stations every 7.2 seconds. WiMAX design is optimized for 0-10 km/h and supports operation up to 120 km/h [11]. RTCA SC223 committee on Airport Surface Wireless Communications [19] is developing "aeroMACS" datalink standard which is based on WiMAX technology and is designed for takeoff and landing applications. The takeoff and landing speeds are in the range of 100-170 nautical miles/h [20]. Aeronautical datalinks for other phases of flight have to be designed for planes traveling at 600 nautical miles/h or 1080 km/h. Again these high speeds result in a high Doppler spread and affect the spectral efficiency.

TABLE I
FREQUENCY BANDS

Band	Frequency
HF	3-30 MHz
VHF	30-300 MHz
UHF	300-1000 MHz
L	1-2 GHz (General) 950-1450 MHz (IEEE)
S	2-4 GHz
C	4-8 GHz
X	8-12 GHz
Ku	12-18 GHz
K	18-26.5 GHz
Ka	26.5-40 GHz

C. Frequency Spectrum

Table 1 lists some of the common frequency bands used in wireless communications. Aeronautical communications systems have traditionally used high-frequency (HF) and very high frequency (VHF) bands as well as higher frequency bands used for satellite communications (SATCOM). However, SATCOM systems are not always available during all phases of flight and the HF and VHF bands are getting very congested. Given the growth in UAS applications and the air traffic, it has become necessary to identify new spectrum for air-to-ground data links. The L-Band, which is already used for several other aeronautical communication functions and has recently become available for Aeronautical Mobile Route Service (AMRS), has been tentative designated as the next desired band.

D. Impact of Moving from VHF to L-Band

It is helpful to first understand the effect of frequency on the datalink design. Lower frequency bands are generally preferred. However, they are getting crowded and so the general trend is to move up in frequency. The crowding in HF band made aeronautical datalinks to move to VHF band and now crowding in VHF band is making us move to L-band. These higher frequency bands are wider and, therefore, can allow wider channels required for higher data rates needed today.

The most basic relationship in wireless link is shown in the equation below. This equation gives the power received (P_R) for a given power transmitted (P_T) at a given wavelength (λ):

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2$$

Here, d is the distance, G_T is the gain of the transmitting antenna and G_R is the gain of the receiving antenna. The wavelength (λ) is given by:

$$\lambda = \frac{c}{f}$$

Where c is the speed of light and f is the frequency. These equations indicate that the path loss is proportional to the square of frequency and distance product:

$$\text{Path Loss} \propto (fd)^2 \tag{1}$$

That is, if we go up 10 times in frequency, the loss will go up by a factor of 100 or we need to decrease the distance by a factor of 10. Note that the Equation 1 is a theoretical approximation. In practice, the distance exponent is more than 2 (between 2 and 5) [32]. One consequence of the above is that the power required to cover the same distance at higher frequency is much more than those at lower frequencies. Stated differently, given the similar amount of power, the signal level is significantly reduced and so the spectral efficiency (bps/Hz) has to be reduced to allow the lower signal-to-noise ratio (SNR). Since higher frequencies do not travel very far, the cell sizes are smaller and so there are more opportunities for frequency reuse.

The second effect of higher frequency is due to Doppler spread.

$$\text{Doppler spread} \propto \frac{v}{\lambda}$$

Here v is the velocity in m/s and λ is the wavelength in m. Again, lower frequencies have longer wavelength and result in smaller Doppler spread. They are better suited for high-speed mobility applications.

The antenna size required is proportional to wavelength. Therefore, higher frequencies need smaller antenna and are preferable for that reason in applications where the mobile station is a small handheld device as is the case in cellular applications.

Another consideration in selecting a frequency band is the effect of weather. Some of frequencies, e.g., 28 GHz band, are affected by rain fall.

IV. SUITABILITY OF L-DACS1 AND L-DACS2 FOR UAS

Two groups both funded by EUROCONTROL - the European organization for the Safety of Air Navigation - have developed two separate proposals: L-Band Digital Aeronautical Communication Systems of Type 1 (L-DACS1) and Type 2 (L-DACS2) for commercial aviation. Although, they have not been formally approved for standardization and were not developed for UAS, they are frequently mentioned in UAS aeronautical communication documents as potential candidates for adoption. In this section, we provide a very brief overview of these proposals and analyze their strengths and weaknesses.

L-DACS1 uses multi-carrier modulation similar to WiMAX. Its physical layer allocation maps and allocation units (tiles and chunks) are similar to those in WiMAX.

L-DACS2 is based on GSM. It uses GSM physical layer. It uses GMSK (Gaussian Minimum Shift Keying) modulation used in the original GSM. Later enhancements to GSM, such as GPRS and EDGE use more aggressive coding but they are not part of L-DACS2. GSM works at 900 MHz, 1800 MHz, and 1900 MHz bands. L-DACS2 is designed to use a single 200 kHz channel in 960-975 MHz band. This is very close to the GSM900 band and so most of the GSM design parameters can be reused in L-DACS2. This design also allows reuse of the volume GSM components resulting in low-cost implementations.

In the following we compare the two L-DACS systems based on modulations, spectral efficiency, and duplexing.

TABLE II
PARAMETERS OF L-DACS1 OFDM

Parameter	Value
Channel bandwidth B	498 kHz
Length of FFT N_c	64
Used sub-carriers	50
Sub-carrier spacing (498/51 kHz) f	9.76 kHz
OFDM symbol duration with guard T_{og}	120 μs
OFDM symbol duration w/o guard T_o	102.4 μs
Overall guard time duration T_g	17.6 μs

A. UAS Speed

As shown in Fig. 1, L-DACS1 is based on B-AMC, P34 and WiMAX. It borrows the overall protocol stack, media access control cycle (uplink and downlink regions), and datalink service protocol from B-AMC. The control message formats and addressing scheme is from P34. Physical layer allocation maps and allocation units (tiles and chunks) are from WiMAX.

The parameters of L-DACS1 OFDM system are shown in Table 2. The key parameter is the subcarrier spacing of 9.76 kHz. This results in symbol duration of 1/9.76 or 102.4 μs. Adding a guard time of 17.6 μs results in an overall symbol duration of 120 μs. The total channel width is 51x9.76 kHz or 498 kHz. This is implemented using 64-FFT (which is the closest power of 2 larger than 50).

The most important parameter is the subcarrier spacing. The OFDM symbol duration is inversely proportional to this spacing. Smaller subcarrier spacing allows larger symbols resulting in lower inter-symbol interference. However, closer spacing carriers can result in increased inter-carrier interference due to Doppler shift.

The sub-carrier spacing of 9.76 kHz in L-DACS1 is similar to that of WiMAX which is optimized for 0-10 km/h and provides functional support for speeds up to 120 km/h (p. 43 of [31]). At WiMAX carrier frequency of 2.5 GHz and vehicular speeds of 100 km/h the maximum Doppler spread is 231.5 Hz. Long Term Evolution (LTE) – the next generation of 3G cellular system – is designed to provide functional support up to 350 km/h and hence uses a larger subcarrier spacing of 15 kHz. The Doppler spread in this case is 300 Hz at 2 GHz and speed of 162km/h (p. 290 of [30]).

For L-DACS1, at 600 nm/h and 1164 MHz (the highest frequency for L-DACS), the Doppler spread is 1213 Hz, which is significantly higher fraction of the subcarrier spacing compare to those for WiMAX or LTE. More analysis is needed to check whether larger subcarrier spacing is required to support the required aircraft speeds of 600 nm/h.

B. UAS Distance

The second important OFDM parameter is the cyclic prefix which is designed to overcome delay spread caused by multipath propagation. Since the radio waves travel at the speed of light, a cyclic prefix of 17.6 μs allows a path differential of 5.28 km. This is the maximum allowed difference between the longest path and the shorted path between the transmitter and receiver. A higher delay spread than this will cause inter-symbol interference. The path length can be much larger than this but the differential generally increases with larger coverage distances. Compare this differential to LTE which uses a normal cyclic prefix of 4.69 μs and extended cyclic prefixes of 16.7 μs and 33.3 μs providing protection against multi-path delay spread of 1.4 km, 5 km, and 10 km, respectively (p. 62 of [30]).

C. Single-Carrier vs. Multi-Carrier Modulations

The current trend in wireless communication is towards multi-carrier modulation using OFDM. OFDM is a special case of frequency division multiplexing (FDM) in which the subcarriers use a sinc (sin(x) /x) power profile and are positioned such that at the peak point of each carrier, the sum of all other subcarriers is zero. This is why it is called orthogonal. OFDM allows using wide channels and a linear growth in throughput with the channel width. Each subcarrier can be modulated differently based on the noise and interference at that frequency. The smaller data rate of each subcarrier results in symbols that are large (in time and hence distance) and are less susceptible to inter-symbol interference caused by signal reflections.

DSP (Digital Signal Processing) chips have made OFDM possible. It can be easily implemented using FFT (Fast Fourier Transform) and IFFT (Inverse Fast Fourier Transform). OFDM is used in 802.11a/g/n WiFi networks, 802.16d/e/m WiMAX networks, LTE (Long Term Evolution) cellular networks, and wired DSL (Digital Subscriber Line).

OFDM is currently considered superior to single-carrier modulation [28]. It degrades gracefully if the channel delay is excessive. It is very robust against frequency selective errors since the affected subcarriers can be easily omitted. Other carriers are coded according to channel conditions. A selected subset of subcarriers is used as a pilot to measure the channel conditions and so there is better channel estimation.

D. Spectral Efficiency

The spectral efficiency of L-DACS1 is 0.6 to 2.76 bps/Hz in the forward (ground to aircraft) direction and 0.44 to 2.08 bps/Hz in the reverse direction. Using 498 kHz channel width, this results in 303 to 1373 kbps in the forward direction and 220-1038 in the reverse direction [29].

L-DACS2 claims to have a spectral efficiency of 1.3 bps/Hz resulting in 270 kbps using 200 kHz in forward and reverse direction combined [3]. This is the raw bit rate. The net data rate after all error correcting codes and overheads may be much lower (approx 1/3rd).

E. Duplexing (TDD vs. FDD)

The next issue is that of duplexing or using the spectrum for bidirectional communication. The two common methods are frequency division duplexing (FDD) and time division duplexing (TDD).

In FDD, two different frequency channels are used for forward and reverse direction. Both directions operate all the time. Since the amount of spectrum in each direction is fixed, the ratio of traffic in the two directions is also fixed. For one-to-one voice communication, the uplink rate is always equal to the downlink rate since everyone is either speaking or listening. So the networks for voice communications (e.g., the cellular networks) are designed for symmetric traffic rates and use the same size channel width in both directions.

In TDD, one frequency channel is shared between the two directions. Some time is reserved for ground to aircraft communication and then some time is reserved for aircraft to ground communication. In the first time zone, all aircraft listen while in the second time zone the aircraft take turns transmitting as indicated by the ground station.

For data applications TDD is considered superior to FDD . This is because the duration of the two directions can be set according to desired uplink to downlink ratio. This is more suitable for data traffic, which is highly asymmetric.

Second, the receiving side can estimate the channel condition by looking at the error statistics. In FDD, the receiver has to send the channel estimation results to the transmitter which can use it to adjust its transmission. In TDD, both sides are receiving on the same frequency and so the channel estimation is faster and easier.

Third, TDD does not require paired spectrum. Given the spectrum congestion, in many cases, it is easier to find one free block of spectrum for TDD than to find two suitably located (paired) blocks.

Although TDD allows uplink to downlink traffic ratio to be adjusted, this ratio is generally not dynamically varied. The ratio is set at the network design time and then kept fixed throughout the life of the network. This is because all neighboring cells need to use the same ratio and to synchronize their networks so that all cells have the uplink regions at the same time and downlink regions at the same time. This is because an aircraft transmitting during the downlink portion of its cell will not be heard if another nearby ground station is transmitting at the same time. Most common uplink to downlink ratio used in traditional networks (WiMAX and LTE) is 2:1. That is, the base stations transmit for twice as long as they receive.

With TDD, all the stations are either transmitting or receiving and so many of the radio components can be shared between the two directions to reduce the cost. A variation of FDD that allows similar flexibility is HFDD (half frequency division duplexing) in which frequency division duplexing is used but a mobile station does not transmit when it is receiving. A FDD system can be operated in the HFDD mode and it is also possible to have a mixture of half-duplex and full-duplex mobiles in the same system. The ground station will have to schedule the aircraft transmissions accordingly.

It is for these reasons, that most of the newer wireless networks, such as WiMAX and LTE allow and preferably use TDD. Since L-DACS is being designed for voice and data communication and data traffic is expected to increase, TDD may be a better fit for this environment.

L-DACS1's choice of FDD seems to be purely based on spectrum availability. It is difficult to find one block of 1 MHz spectrum in some parts of the L-Band and so the designers decided to use FDD and require two blocks of 0.5 MHz each. However, FDD does limit it to symmetric traffic (the rates in two directions are different because of different power levels) which may be seen as too constraining. Recent upcoming standards such as WiMAX v2 (IEEE 802.16m) and LTE-advanced use “multi-carrier aggregation” and allow multiple non-adjacent channels to be used as one channel [10]. If adopted for L-DACS1, this may allow L-DACS1 systems to use several unused spectrum spaces in the L-band in one system and meet the capacity and asymmetry required for data using TDD. This, therefore, needs further study.

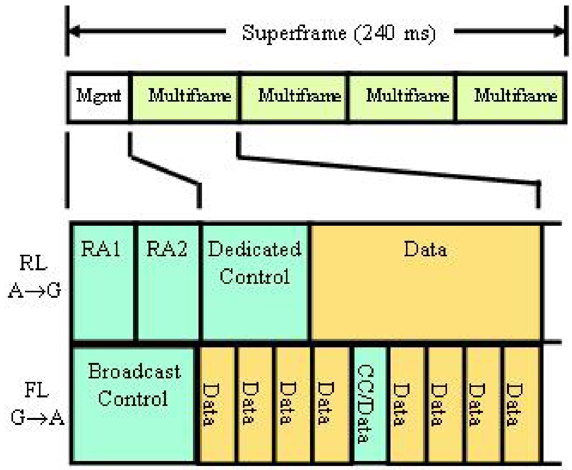

Fig. 2. L-DACS1 physical layer framing

F. Physical Layer Framing

1) L-DACS1: Fig. 2 shows the physical layer framing for L-DACS1. The time is divided into 240 ms intervals called superframes. In the forward link, each superframe begins with a 6.72 ms broadcast control region in which the ground station announces the network parameters and transmission and reception opportunities allocated to various aircraft which have joined the network. The remainder of the forward link is divided in to 4 multiframes, each of which consists of nine 6.48 ms slots. Eight of these slots are used for data and one may be used for common control or data. In the reverse direction, the first 6.72 ms slot is reserved for two random access opportunities for new aircraft to join the network. It is followed by 4 multiframes, each of which consists of a dedicated control region and data region. Each aircraft has a reserved transmission opportunity in the dedicated control region. They can use this opportunity to request additional transmission opportunities based on their traffic. The ground station allocates the data region accordingly.

As indicated in Table 2, each OFDM symbol is 120 μs long. So the superframe consists of 2000 OFDM symbols, the broadcast control consists of 56 symbols, each forward link data transmission slot consists of 54 symbols or 3 PHY PDUs of 18 symbols each. The common control is also 54 symbols.

2) L-DACS2: As shown in Fig. 3, in L-DACS2, the time is divided in to 1 second frames. Each frame is divided in two uplink (Ground to Aircraft) sections, two downlink (Aircraft to Ground) sections, and one login section for new aircraft wanting to join the network.

This frame structure is similar to that in E-TDMA and AMACS. The first uplink section UP1 also contains a broad-

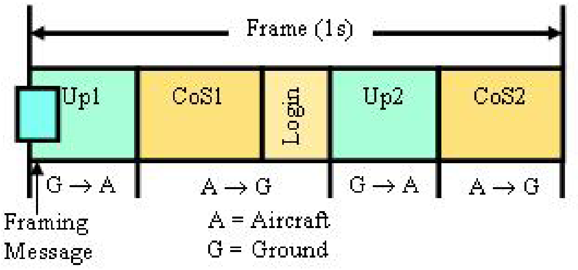

Fig. 3. L-DACS2 Physical Layer Framing

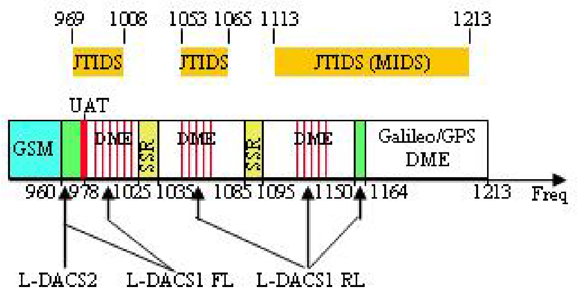

Fig. 4. L-band spectrum usage

cast region that contains the map of the rest of the frame and allows aircraft to determine their transmission and reception opportunities. The first downlink section CoS1 has a reserved slot for each aircraft, which they can use to make requests for additional transmission opportunities required. The second downlink section CoS2 is allocated accordingly.

Note that the uplink and downlink section sizes are changeable only at the network design time. This is because all neighboring cells have to synchronize their uplink and downlink sections. Any change in the section sizes have to be coordinated. Otherwise, the high powered uplink transmissions in one cell will interfere heavily with the low-powered downlink transmissions from aircraft.

G. Interference Properties

Fig. 4 shows the L-band spectrum usage. The band is shared by DME (distance measuring equipment), SSR (secondary surveillance radar), JTIDS (Joint Tactical Information Distribution System) and MIDS (Multifunction Information Distribution System). GSM900 is adjacent to the lower edge of the spectrum.

DME ground markers are assigned 1 MHz band in the regions marked for DME. So other parts of the band may be available for aircraft wireless datalinks. Fig. 4 shows the forward and reverse link spectrum possibilities for L-DACS1 and L-DACS2. Note that L-DACS1 needs a paired spectrum with 63 MHz spacing between the forward and reverse links. L-DACS2 will need a 200 kHz channel in the lower L-band 960-975 MHz region.

A thorough analysis of potential levels of interference from these various technologies can be found in [23]. Of these interfering technologies two that are most serious are DME and GSM because of their high powered transmissions. DME and L-DACS antennas on the aircraft can interfere significantly.

TABLE III
INTERFERENCE BETWEEN GSM AND L-DACS

	L-DACS1	L-DACS2
Transmitted power (over 200 kHz)	43 dBm	43 dBm
Transmitter Antenna gain	19 dB	19 dB
Frequency difference from Carrier	-80 dB (> 6 MHz)	-70 dB (0.6-1.2 MHz)
Reception Bandwidth	+7 dB (500 kHz/100 kHz)	+8.2 dB (200 kHz/30 kHz)
Subtotal	-11 dB	+0.2 dB
Distance (Collocated)	-30 dB	-30 dB
Receiving antenna gain	+19 dB	+19 dB
Total	-22 dBm	-10.8 dBm

Similarly, GSM base stations and ground L-DACS stations can interfere. These two cases are discussed in this section.

1) Interference between DME and L-DACS: DME consists of ground DME markers on the airstrip that transmit 1 to 10 kW EIRP (equivalent isotropic radiated power). The aircraft DME equipment transmits approximately 700 W or 58.5 dBm. The DME Antenna and the L-DACS antenna located on the same aircraft would interfere with each other. In the worst case, allowing a 35 dB loss for the short path between the two antennas, the L-DACS could see an interference of 23.5 dBm. This is a significant amount of interference and we need to design a coexistence strategy.

2) Interference between GSM and L-DACS: Interference from GSM towers is also significant. The GSM base stations are allowed to transmit up to 62 dBm EIRP which is the sum of antenna gain and the transmitted power. For example, a base station with 19 dBi antenna can transmit up to 43 dBm power.

Table 3 shows the net interference from such a transmission on a nearby L-DACS ground station. The net interference is –22 dBm for L-DACS1 and –10.8 dBm for L-DACS2. L-DACS2 is affected more primarily because its frequency spectrum is very close to that used by GSM. This analysis assumes only one GSM tower. In practice there may be several GSM base stations belonging to different service providers in the airport area.

H. Summary of Comparison between L-DACS1 and L-DACS2

In this section we have surveyed the key features of the two proposals for L-band digital aeronautical communication systems (L-DACS). We are not associated with either of the two design teams and so this is one of the few independent comparisons of the two systems. Our conclusions are as follows:

1. L-DACS1 with OFDM is more scalable than L-DACS2 with single carrier modulation. Although as specified, both L-DACS1 and L-DACS2 use fixed spectral width, L-DACS1 can be easily scaled up to fit any available width.

2. L-DACS1 also has better spectral efficiency because it can use adaptive modulation and coding (QPSK through 64 QAM) depending upon the noise and interference pattern.

Single carrier modulation and GMSK used by L-DACS2 do not easily adopt to dynamic noise conditions.

3. Multi-carrier design of L-DACS1 is also more flexible in terms of spectrum placement. With proper profile (parameter set), it can use any available white space in the L-band. Single-carrier radios of L-DACS2 would find it more difficult to adapt to different frequency possibilities.

4. Multi-carrier design of L-DACS1 is also more suitable for interference avoidance and co-existence than L-DACS2.

5. The TDD design of L-DACS2 allows for asymmetric data traffic. The FDD design of L-DACS1 is suitable for symmetric voice traffic but less suitable for data. Also requiring a frequency pair separated by 63 MHz may make it harder to find suitable frequencies. The asymmetry of the control data traffic needs to be studied. Multi-carrier aggregation introduced in IEEE 802.16m can be used in L-DACS1 to overcome the problem of availability of adjacent spectrum availability and use TDD.

6. The cyclic prefix and subcarrier spacing of L-DACS1 need to be analyzed to ensure that they will cover the distance and speeds required for ENR region operation.

7. GSM900 stations may cause significant interference with the L-DACS systems. Again L-DACS2 is more susceptible to such interference because its proposed spectrum is very close to that of GSM. The effect of multiple GSM transmitters near the L-DACS ground stations needs to be analyzed.

V. Other Issues in UAS Datalink Design

A. High-Availability

One of the most critical requirements for UAS is the ability to "Sense and Avoid." That is, if an object is sensed nearby, the remote pilot should be able to avoid it. The normal definition of availability – the ratio of mean uptime to total time is not meaningful in such situations. For example, consider two systems – one with very small uptimes and small downtimes and another with large uptimes and large downtimes. Both these systems may have the same availability but the system with small uptime may not be very useful since it fails so frequently and may not be able to complete any transactions.

This issue was discussed in the SC203 committee and an alternative metrics called "Continuity" was proposed which is defined as follows:

$$\text{Continuity} = \frac{\sum_i (\text{Uptime}_i | \text{Uptime}_i > T_c)}{\text{TotalTime}}$$

Here, T_c is the transaction completion time. This definition also ignores the large downtimes that can be deadly in the case of UAS. Also, this expression is not the probability of transaction completion either. Successful transaction completion requires that the transaction begin at least T_c units of time before the end of uptime and, therefore,

$$\text{P(TransactionCompletion)} = \frac{\sum_i (\text{Uptime}_i - T_c | \text{Uptime}_i > T_c)}{\text{TotalTime}}$$

The problem with this probability is that it assumes that the risk is proportional to the downtime. This is true in many other applications. However, for sense and avoid applications, the risk increases significantly if the downtime exceeds a certain threshold.

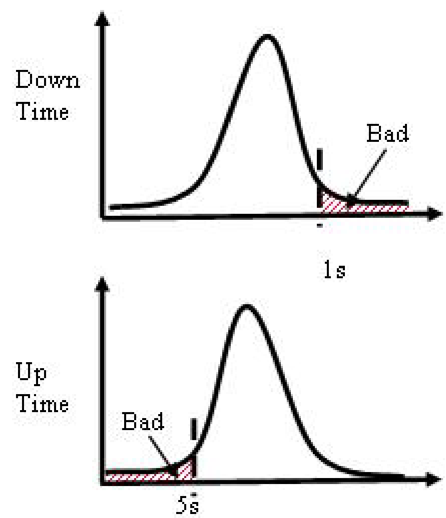

Fig. 5. Percentiles of downtime and uptime are better metric for sense and avoid applications than availability

For sense and avoid application, large downtimes as well as small uptimes are bad. Therefore, it is important to limit the probabilities of large downtime and small uptimes (See Fig. 5).

This leads to the conclusion that the best metric to measure the availability for UAS sense and avoid applications is some percentile, say, 99.999th percentile of the downtime and 0.001th percentile of the uptime. For a good system, the 99.999th percentile of downtime should be low and the 0.001th percentile of the uptime should be high. Given these two numbers it is easy to compute the risk.

B. Networked Controller

It is normally assumed that the UAS is communicating with a wireless ground station with the human controller sitting right at the base station. This would generally be the case for small UASs in remote areas particularly in military applications. This is the non-networked controller scenario.

Another possibility is that the human controller is connected to the base station via a ground network. In this case, the ground station is part of a nationwide system of base stations and towers that coordinate with each other. In this case, there is a possibility of a smooth handover of UAS from one ground station to next. This is called "Networked" Controller scenario. The datalink needs to support both networked and non-networked scenarios.

C. Overload Control and Preemption

Regardless of what design is used, there would be situations when the number of UASs communicating with the ground stations exceeds the nominal capacity. In these cases, it is important that the users with more critical services (such as sense and avoid) be given priority over those with less critical services (video surveillance). So a priority system is required that will allow lower priority services to be delayed or preempted to make way for high-priority services.

D. Chaining

Chaining, also known as multi-hopping, refers to the case of an UAS helping another UAS to reach the ground station. The chain could consist of more than two UASs. This application is important for areas where there is no ground infrastructure such as in military environments.

E. Compatibility and Co-Existence with Manned Aircraft

It is important that the UAS datalink architecture be compatible with that used for manned aircraft since both of them will be sharing the same frequency bands and the same airspace. The traffic requirements envisioned for future manned aircraft communications are currently significantly higher than those for unmanned aircraft.

The requirements for manned aircraft are specified in COCR (Communications Operating Concept and Requirements) V2 [14] which specifies two phases. The first phase begins now and the second phase begins in 2020 after which both phases will continue till 2030. COCR specifies a peak instantaneous aircraft counts (PIACs) in the range of 200 to 300 aircraft for high-density airports. The UAS requirements are only in the range of 20 aircraft per ground station. So it would be difficult to use the same design for both manned and unmanned systems. This would introduce a compatibility issue where the two systems will not be able to communicate with each other or the same ground stations.

VI. Interference Mitigation and Coexistence Strategies

One problem with L-Band is that the band is already used by several aeronautical applications (See Fig. 4). These applications will interfere with each other.

Multiple wireless technologies sharing spectrum is very common in unlicensed band. For example, Bluetooth and WiFi share the 2.4 GHz band. Most laptop computers today are equipped with both Bluetooth and WiFi. The coexistence strategies used by them [15] can be used for UAS as well. In this section, we propose such strategies.

A. Collaborative Co-Existence of DME and L-DACS

Aircraft may have multiple wireless datalinks, e.g., both DME and L-DACS. As indicated earlier the two antennas will interfere significantly. Since both equipments are on the same aircraft, it is possible to design the two systems so that they collaborate in avoiding the mutual interference. One simple strategy is to divide the time so that when DME stations are transmitting or receiving, the L-DACS system is quiet and when L-DACS is transmitting or receiving DME is quiet.

These strategies assume that aircraft DME system can be redesigned to accommodate L-DACS technology and the aircraft are refitted with this updated version of DME. This may or may not always be feasible. We do not assume any changes to ground DME systems. The aircraft would have a common controller for the two systems and would dynamically determine the time allocation between the two depending upon the traffic. The aircraft L-DACS system will inform the ground station of unavailable times so that it will schedule transmission and reception opportunities for that aircraft accordingly.

In case of L-DACS1, it is also possible to notch out (not use) the subcarriers that are affected by the interference. In this sense, L-DACS1 is more resistant to interference and thus more survivable even under interference conditions.

B. Non-Collaborative Coexistence Strategies

If the DME system cannot be modified, the L-DACS system will have to use non-collaborative strategies. This would require L-DACS system to measure the interference pattern (time and frequency) and adjust its transmission and reception accordingly.

The interference and noise can be distinguished by the bit error patterns. Interference results in bursty errors while noise results in random errors. FEC can take care of random errors but bursty errors require retransmissions. So FEC may not be used if there is excessive interference. The resulting extra bits can be used for retransmission.

The L-DACS1 system can keep track of subcarriers on which there is excessive interference and not use them. Again, we find that L-DACS1 system is more interference resistant and more survivable than L-DACS2 system.

VII. Summary

In this paper, we have presented the challenges, requirements, and issues in designing datalinks for UAS. The two key challenges are: Long distances, high-speed. Covering these distances and aircraft speeds affects the efficiency of the datalinks. Significant changes to carrier spacing in multi-carrier modulations, e.g., OFDMA, is required to cover these speeds.

We also discussed the suitability of L-DACS1 and L-DACS2 proposals, which are commonly mentioned as candidates for the next generation aeronautical communications. Our conclusion is that a design with multi-carrier modulation and time-division duplexing would be more suitable than these two. SC203 committee on Unmanned Aircraft Systems is already working on such a design.

Other requirements that the UAS datalink design needs to meet are:

1) High-availability: We need new metrics to allow risk assessment for sense and avoid applications.
2) Networked and Non-networked controllers: Both cases need to be covered.
3) Preemption: Need a multi-priority design to allow urgent communications to continue.
4) Chaining: To allow UASs to communicate to ground stations via other UASs
5) Compatibility with manned aircraft datalinks

Finally we showed how multiple aeronautical applications using the same L-Band can co-exist and avoid interference using collaborative and non-collaborative strategies.

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