Analysis of L-Band Digital Aeronautical Communication Systems: L-DACS1 and L-DACS2

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Abstract— New air-to-ground wireless datalinks are needed to supplement existing civil aviation technologies. The 960 - 1164 MHz part of the IEEE L band has been identified as a candidate spectrum. EUROCONTROL – the European organization for the Safety of Air Navigation, has funded two parallel projects and developed two proposals called L-DACS1 and L-DACS2. Although, there is a significant amount of literature available on each of the two technologies from the two teams that designed the respective proposals, there is very little independent comparison of the two proposals. The goal of this paper is to provide this comparison. We compare the two proposals in terms of their scalability, spectral efficiency, and interference resistance. Both the technologies have to co-exist with several other aeronautical technologies that use the same L-band. [1 2]

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1. INTRODUCTION

There are a number of wireless technologies that are used for a variety of purposes in aeronautical applications. This includes distance measurement, surveillance beaconing, collision avoidance, passenger telephones, etc. This paper deals with aviation data link technologies that support data communications between the plane, Air Traffic Control (ATC), Aeronautical Operational Control (AOC) and Airline Administrative Control (AAC).

Two groups, both funded by EUROCONTROL, the European organization for the Safety of Air Navigation, have made separate proposals called L-Band Digital Aeronautical Communications System Type 1 (L-DACS1) and Type 2 (L-DACS2). This paper surveys the features of these two proposals and analyzes their strengths and weaknesses.

2. EVOLUTION OF AERONAUTICAL WIRELESS DATALINKS

In order to understand the features and design decisions of the two L-DACS proposals, it is helpful to understand the past evolution of aeronautical datalinks. This is shown in Figure 1.

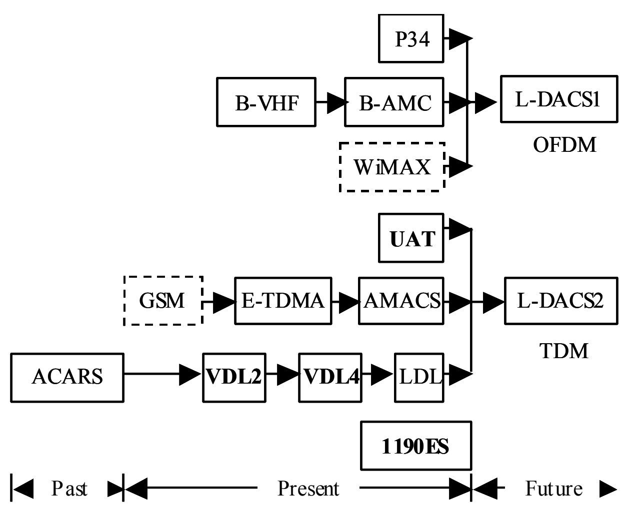

Figure 1: Evolution of Aeronautical Datalinks

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

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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 [9] 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) [7] 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 aircrafts 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 aircrafts 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 [8]. 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.

3. L-DACS FUNCTIONAL ANALYSIS

3.1 L-DACS1 and L-DACS2 Overview

L-DACS2 is based on GSM, UAT, and AMACS. It uses GSM physical layer and AMACS media access control (MAC). L-DACS2 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 GSM 900 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.

As shown in Figure 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 1. 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. Larger symbols result in lower inter-symbol interference. However, closer spacing carriers can result in increased inter-carrier interference due to Doppler shift.

Table 1: Parameters of L-DACS1 OFDM

Parameter	Value
Channel bandwidth B	498 kHz
Length of FFT Nc	64
Used sub-carriers	50
Sub-carrier spacing (498/51 kHz) f	9.76 kHz
OFDM symbol duration with guard Tog	120 µs
OFDM symbol duration w/o guard To	102.4 µs
Overall guard time duration Tg	17.6 µs

The sub-carrier spacing of 9.76 kHz in L-DACS 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 [18]). 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 [19]).

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.

The second important OFDM parameter is the cyclic prefix which is designed to overcome delay spread caused by multi-path 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 use 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 [18]).

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

3.2 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 [16]. 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.

3.3 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 [17].

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 [4]. This is the raw bit rate. The net data rate after all error correcting codes and overheads may be much lower (approx 1/3rd).

3.4 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 aircrafts listen while in the second time zone the aircrafts 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 twice as much 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 is 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 [20]. 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.

3.5 Physical Layer Framing

3.5.1 L-DACS1

Figure 2 shows the physical layer framing for L-DACS1.

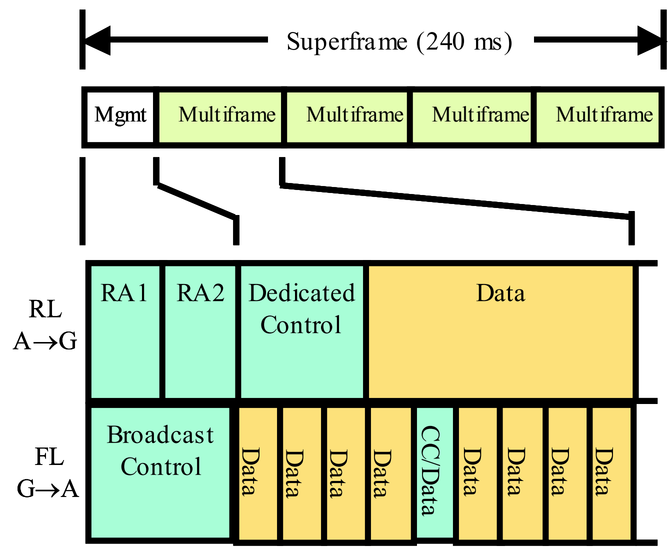

Figure 2: L-DACS1 Physical Layer Framing

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 aircrafts 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 aircrafts 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 1, 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.

3.5.2 L-DACS2

As shown in Figure 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 aircrafts 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 broadcast region that contains the map of the rest of the frame and allows aircrafts 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.

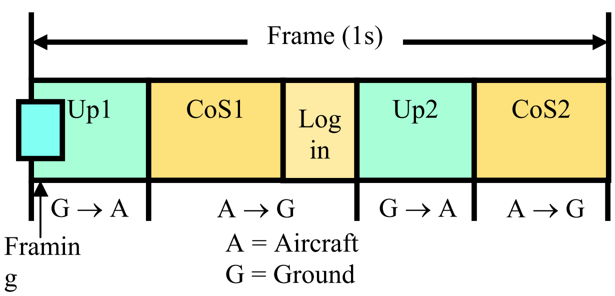

Figure 3: L-DACS2 Physical Layer

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 brown out the low-powered downlink transmissions from aircrafts.

4. Interference Properties

Figure 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 L-DACS. Figure 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.

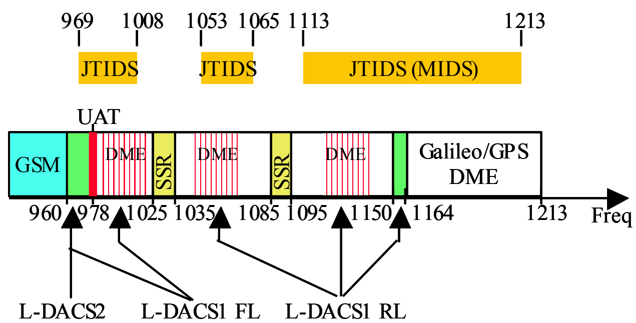

Figure 4: L-Band Spectrum Usage

A thorough analysis of potential levels of interference from these various technologies can be found in [6]. 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. Similarly, GSM base stations and ground L-DACS stations can interfere. These two cases are discussed in this section.

4.1 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.

4.2 Interference between GSM and L-DACS

Interference from GSM towers is also significant. Figure 5 and Table 2 [6] show the transmission mask specified by the GSM specifications.

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.

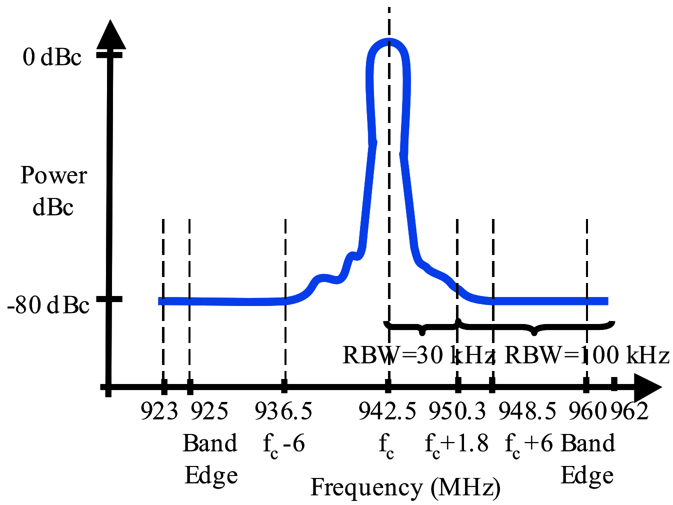

Figure 5: GSM Power Spectrum

Table 2: EIRP for GSM 900

Offset from Carrier (kHz)	Relative Power (dB)
100#	+0.5
200#	-30
250#	-33
400#	-60
600-1200#	-70
1200-1800#	-73
1800-6000*	-75
>6000*	-80

#Measurement bandwidth is 30 kHz.

*Measurement bandwidth is 100 kHz

Table 3: Interference between GSM and L-DACS

	L-DACS1	L-DACS2
Transmitted power (over 200kHz)	43 dBm	43 dBm
Transmitter Antenna gain	19 dB	19 dB
Frequency difference from Carrier	-80 dB (>6MHz)	-70 dB (0.6-1.2MHz)
Reception Bandwidth	+7 dB (500kHz/100 kHz)	+8.2 dB (200kHz/30kHz)
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

5. L-DACS PERFORMANCE ANALYSIS

5.1 Communication Performance Requirements

Requirements for aeronautical datalinks are specified in COCR (Communications Operating Concept and Requirements) V2 [10] which specifies two phases. The first phase begins now and the second phase begins in 2020 after which both phases will continue till 2030. The performance requirements are specified for a number of services in a number of domains, such as: airport (APT), terminal maneuvering area (TMA), en route (ENR), oceanic/remote/polar (ORP), and autonomous operations area (AOA). COCR v2 is 172 pages long. Here we present the key relevant performance requirements.

The peak instantaneous aircraft counts (PIACs) in high-density airports, as specified, are listed in Table 4.

Table 4: PIACS in High-Density Airports

Region	Year	APT	TMA	ENR	ORP
Europe	2020		16	24	
US	2020	200		41	10
Europe	2030		44	45	
US	2030	290		95	34

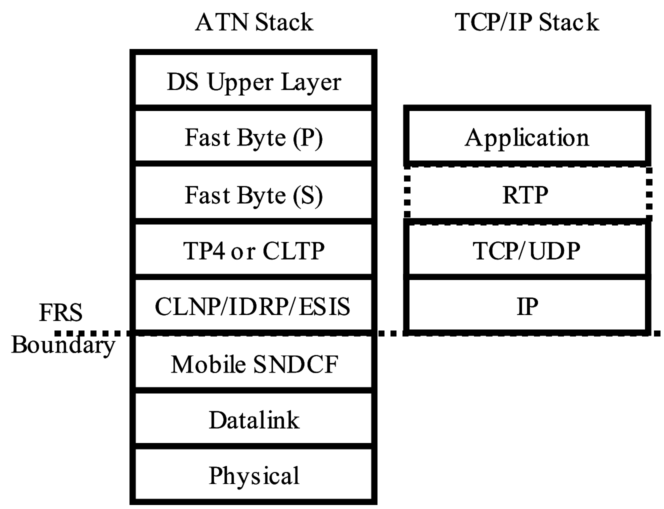

Figure 6: Future Radio System (FRS) Boundary

The maximum aircraft speed in Knots True Airspeed (KTAS) is listed in Table 5.

Table 5: Max Airspeed in KTAS

	APT	TMA	ENR	ORP	AOA
Phase 1	160	250	600	600	
Phase 2	200	300	600	1215	540

COCR does not specify a protocol stack but specifies the packet sizes at the datalink layer assuming ATN stack as shown in Figure 6.

In the ATN stack, the upper layer overhead is 72 bytes. The document lists a number of services, their latency requirements, and the message sizes at the FRS boundary.

The most stringent capacity requirements in kbps are listed in Table 6:

One of the concerns, we have with these requirements is that the data rate targets are too low. These targets have been set based on current usage. Once the datalink is designed the usage will grow in unforeseen ways. These same L-DACS proposals are already being considered for use in unmanned aircraft (UA) applications where control traffic will be significantly higher. One rule of thumb that we have followed in other environments is to design for a growth rate equal to higher than the Moore's law. According to that law, a technology designed with 10X capacity of today's demand will last 3-5 years. This has been the case in IEEE 802.3 Ethernet and IEEE 802.11 WiFi standards. Similar growth rates are planned for IEEE 802.16 WiMAX networks. The aeronautical datalink design would have a very limited lifetime unless we plan for significant growth in data rates.

Table 6: Most Stringent Capacity Requirements in kbps

Phase	APT	TMA	ENR EU	ENR US	ORP	AOA
Phase 1	30	8	15	20	5	
Phase 2	200	40	150	200	40	100

5.2 L-DACS1 Reverse Link Capacity Analysis

Reverse link is always more capacity constrained than forward link because of significant power limitations of the aircraft and the overhead of guard times between the transmissions from multiple aircrafts. In L-DACS1, there are 50 subcarriers and each OFDM symbol time is 120 µs. The reverse link allocation is in terms of tiles which consist of 25 subcarriers over 6 OFDM symbols resulting in a capacity of 150 data symbols per tile. Of these, 134 are used for data and 16 are used for channel estimation and power control.

L-DACS1 has a superframe length of 240 ms. Each aircraft needs a dedicated control (DC) of one tile, which is used to request bandwidth for messages. There is an additional synchronization and power control overhead of approximately 1 OFDM symbol time per aircraft. The total per aircraft DC overhead is, therefore, equivalent to approximately 4 OFDM symbol times or 0.48ms. With N aircrafts and allowing 6.72 ms for random access:

RL data capacity per superframe = 240-6.72-0.48N ms
= (233.28-0.48N)/0.120 OFDM symbols
= 1944-4N OFDM symbols
RL data capacity = (1944-4N)/0.240 OFDM symbols/sec
= (8100-16.6N) OFDM symbols/sec
= (8100-16.6N)*(2/6) tiles/sec
= (8100-16.6N)*(2/6)*134 data symbols/sec

The nominal RL data rate will depend upon the modulation used. QPSK1/2 gives 1 bits/data symbol while 64QAM3/4 will give 4.5 bits/data symbol. The resulting capacity in kbps is shown in Figure 7 as a function of the number of aircrafts. There is an additional overhead of control and preambles before each transmission that should be deducted from the capacity shown in this figure. The actual modulation that can be used will depend upon the channel condition and the distance between the ground station and the aircraft. In particular, in the ENR domain, the capacity will be closer to the QPSK ½ line.

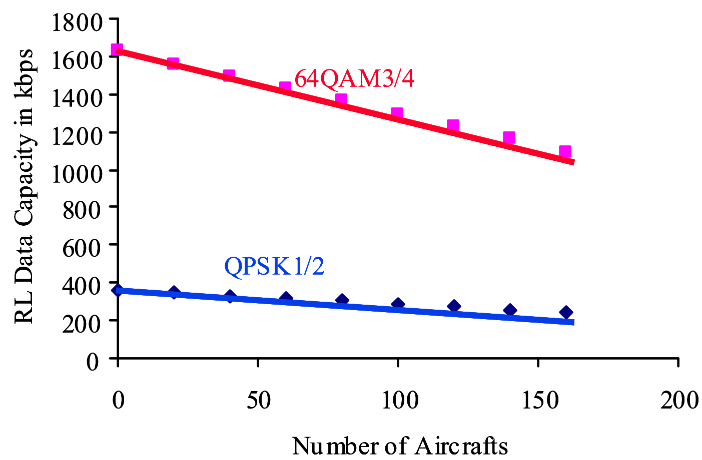

Figure 7: Reverse Link Data capacity of L-DACS1

5.3 L-DACS2 Reverse Link Capacity Analysis

In L-DACS2, each transmission burst begins with an 8-bit ramp up period followed by a 26-bit sync sequence, 8-bit start flag and ends with an 8-bit end flag, 8-bit ramp down, and a guard period as shown in Figure 8.

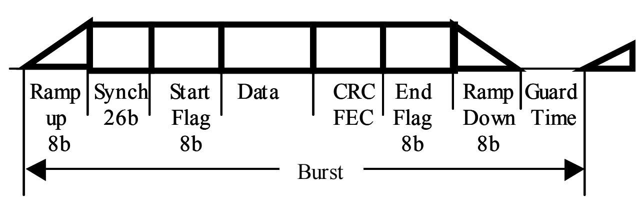

Figure 8: L-DACS2 Burst Structure

The length of the guard period varies depending upon the length of the burst. The guard time can be reduced if the ground station measures the arrival times of burst, computes the propagation delay and provides this information back to the aircraft. This is called adaptive guard time. In this case, the guard time is approximately 34 bit times (Table 18 in [4]). The CRC+FEC bits depend upon the length of the data. Assuming 32b CRC, the total per burst overhead is 8+26+8+16+8+34=116 bits. The CoS2 bursts can be 1 to 10 slots.

L-DACS2 frame is 1 second long and uses GMSK modulation which provides 1.3b/Hz or 270 kbps for 200 kHz for both directions. Frame is divided into 150 slots. So each slot is 1/150s or 1805 bits or 220 bytes. The burst overhead is 0.5% to 5% not including the FEC which in some cases can use as many as one-half of all bits.

Of 150 slots in the frame, a variable number can be used for CoS1 and CoS2. Each active aircraft requires 1/6th of a slot in the CoS1 region. The default number of slots for CoS1 and CoS2 is 13.33 and 66 slots. This allows 80 active aircrafts. With N active aircrafts, the net reverse link capacity is (66+13.33-N/6) slots per frame or (79.33-N/6)*1805 bps. Some these bits are used for FEC. In a normal GSM cell of a few kms, almost 1/3 of the bits are used for FEC. The effective throughput is, therefore, (79.33-N/6)*1204 bps. As the cell size increases, the signal strength and the signal to noise ratio decreases as 2nd to 4th power of the distance. The BER increases and the effective throughput decreases. As a result, in the ENR region with distances in hundreds of kms the capacity will be several orders of magnitude smaller as shown in Figure 9.

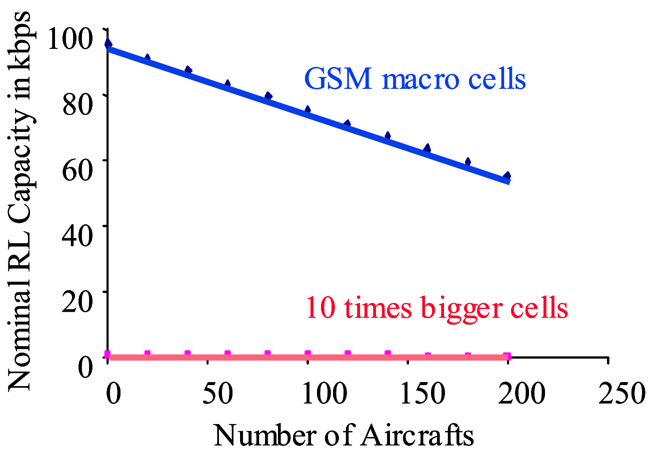

Figure 9: L-DACS2 reverse link capacity

6. CONCLUSIONS

In this paper 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.

7. ACKNOWLEDGEMENTS

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9. List of Acronyms

1090ES	1090 Extended Squitter
8-PSK	8 Phase Shift Keying
ACARS	Aircraft Communications Addressing and Reporting System
ADS-B	Automatic Dependent Surveillance Broadcast
AGC	Automatic Gain Control
AMACS	All Purpose Multichannel Aviation Communications System
AOC	Aeronautical Operation Control
ARINC	Aeronautical Radio, Inc.
AS	Aircraft Station
ATS	Aeronautical Traffic Services
B-AMC	Broadband Aeronautical Multicarrier Systems
B-VHF	Broadband Very High Frequency System
BC	Broadcast Control
CC	Common Control
CDMA	Code Division Multiple Access
CPDLC	Controller-Pilot Datalink Communication
DCH	Data Channel
DME	Distance Measurement Equipment
E-TDMA	Extended Time Division Multiple Access
EIA	Electronic Industries Association

FCI	Future Communications Infrastructure
FDD	Frequency Division Duplexing
FEC	Forward Error Correction
FL	Forward Link (Ground to Airplane)
GHz	GHz
GMSK	Gaussian Minimum Shift Keying
GS	Ground Station
GSM	Groupe Speciale Mobile
HF	High Frequency
JTIDS	Joint Tactical Information Distribution System
L-DACS	L-band Digital Aeronautical Communications System
LDL	L-band Digital Link
MC-CDMA	Multi-carrier Code Division Multiple Access
MHz	Mega Hertz
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
P34	Project 34
PAPR	Peak-to-Average Power Ratio
PHY	Physical Layer
RA	Random Access
SS	Secondary Surveillance
SSR	Secondary Surveillance Radar
TDD	Time division duplexing
TDMA	Time Division Multiple Access
UAT	Universal Access Transceiver
VDL	VHF Digital Link
VHF	Very High Frequency

BIOGRAPHIES

Raj Jain is a Fellow of IEEE, a Fellow of ACM, a winner of ACM SIGCOMM Test of Time award, CDAC-ACCS Foundation Award 2009, and ranks among the top 50 in Citeseer's list of Most Cited Authors in Computer Science. Dr. Jain is currently a Professor of Computer Science and Engineering at Washington University in St. Louis. Previously, he was one of the Co-founders of Nayna Networks, Inc - a next generation telecommunications systems company in San Jose, CA. He was a Senior Consulting Engineer at Digital Equipment Corporation in Littleton, Mass and then a professor of Computer and Information Sciences at Ohio State University in Columbus, Ohio. He is the author of ``Art of Computer Systems Performance Analysis," which won the 1991 ``Best-Advanced How-to Book, Systems" award from Computer Press Association. He is a co-editor of "Quality of Service Architectures for Wireless Networks: Performance Metrics and Management," published in April 2010.

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