THE CAPACITY AND PERFORMANCE OF A CPDLC SYSTEM USING VDL MODE E

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Abstract

VDL Mode E is a digital TDMA communications system proposed as a global standard for replacement of the 8.33 kHz and 25 kHz analog AM systems currently used for VHF aeronautical communications. VDL Mode E is spectrum compatible with 8.33 kHz analog channels, providing an orderly phased-in upgrade of either 8.33 kHz or 25 kHz systems to provide increased channel capacity and security for both voice and data link communications.

With air traffic communications migrating to data link systems, such as the VDL Mode 2 Link 2000+ CPDLC network in Europe, it is important that any new system provide adequate performance and capacity for this type of communications.

The paper provides an overview of the design and estimation of capacity of a proposed data link configuration of VDL Mode E optimized for CPDLC operation. It shows that the capacity provided will exceed that needed to support the forecasted levels of European air traffic through the year 2050.

Introduction

To solve current frequency congestion issues, a replacement is needed for the current 8.33 kHz and 25 kHz analog AM VHF aeronautical communications systems. VDL Mode E is one of several systems being considered by the Future Communications System (FCS) study group [1] as a global standard for a new aeronautical communications system.

VDL Mode E is a digital TDMA system that operates on 8.33 kHz channels [2]. Because of the 8.33 kHz spectrum compatibility, it can be easily integrated within the 8.33 and 25 kHz based communications infrastructures in place at the time of its introduction. There is no need for sub-bands as with other proposed VHF systems. As will be shown, the VDL Mode E voice and data link services will be scaleable to meet the growth in Peak Instantaneous Aircraft Count (PIAC) to at least the year 2050.

VDL Mode E Characteristics

VDL Mode E will support aeronautical mobile voice and data link communications with a line of sight range in excess of 200 nmi. For each 8.33 kHz channel, VDL Mode E provides two independent TDMA digital circuits and associated management channels. On 8.33 kHz channels, the two circuits can be used for any combination of voice or digital data. When implemented on 25 kHz channels, three VDL Mode E channels can be used to provide 6 independent digital circuits.

VDL Mode E is based on the 25 kHz channel based VDL Mode 3 system developed by the United States Federal Aviation Administration and industry partners. FAA TSO approved avionics are now available from Rockwell Collins that provides multi-mode VHF Communications operations, including VDL Mode 3.

VDL Mode E uses the same D8PSK waveform as VDL Mode 3 with the symbol rate reduced to provide a spectrum that is contained within an 8.33 kHz channel. By re-using the waveform and many of the other key parameters of the proven VDL Mode 3 design, such as the VOCODER and network protocols, the risks associated with complete development of VDL Mode E are greatly reduced when compared to a new system.

VDL Mode E can be implemented by a software upgrade to new multi-mode VHF Communications transceiver recently developed and TSO certified by Rockwell Collins for use in the VDL Mode 3 system. This upgrade path can result in lower avionics cost to users since new hardware development is not required.

Aircraft Data Link

For pilot-controller information exchanges for air traffic control, data link, using a format such as CPDLC, provides a lower pilot workload and a higher integrity alternative to voice communications. As will be shown, the proposed data link configuration of VDL Mode E can be used to provide a very efficient and deterministic data link capability.

Because some form of voice communications will always be required in a data link based system as a backup, the 2V voice configuration of VDL Mode E can be used to provide this capability. The 2V configuration will provide a 100% increase in the voice capacity of the existing 8.33 kHz analog AM system by providing two independent voice circuits on each 8.33 kHz channel [2]. At the time of introduction of VDL Mode E, the 2V configuration can be used to consolidate all voice operations into about 50% of the existing 8.33 KHz analog channels, freeing use of the remaining channels to serve as a foundation for a high capacity data link network using an all-data configuration of VDL Mode E.

Description of VDL Mode E Data Link Configuration

In a two way data link system for ATC use, it is important that the ground and aircraft stations have deterministic, guaranteed access to the channel so that time critical messages can be transmitted. Message latency, for both uplinks and downlinks, is also important and determines the capacity of a channel.

A proposed architecture for a TDMA data link configuration of VDL Mode E, designated 2D, is shown in Figure 1. It provides the required guaranteed access capability and also meets the message latency requirements given in the Eurocontrol "MACANDO" document [3].

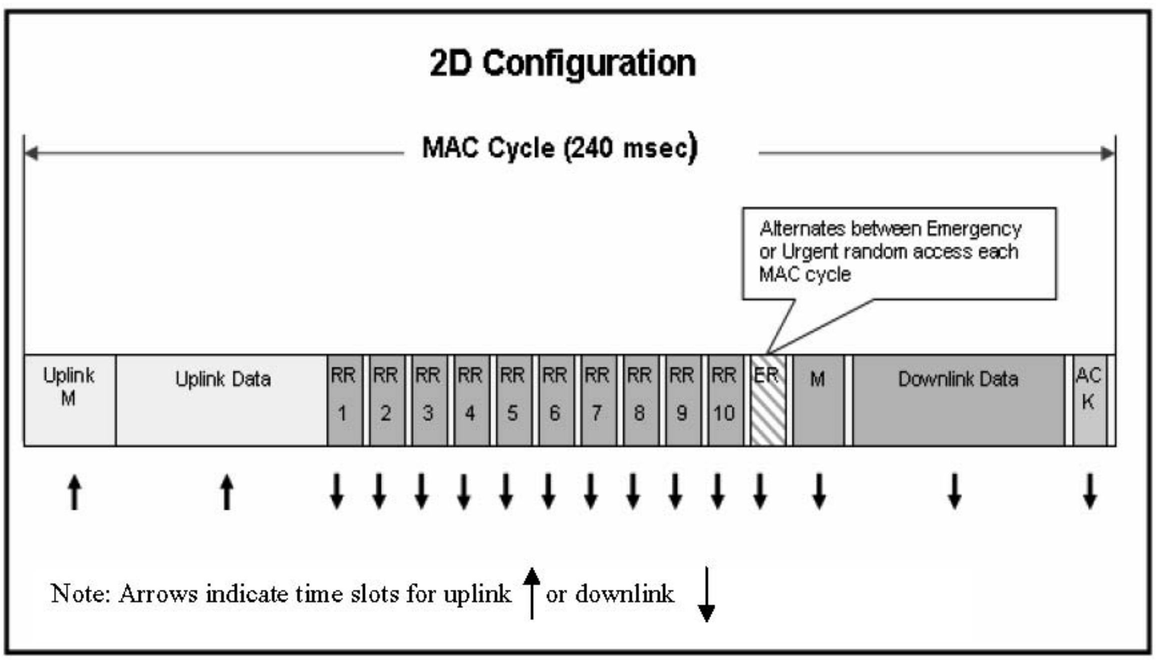

Figure 1. 2D Configuration of VDL Mode E

The basis for the 2D configuration is a Media Access Control (MAC) cycle. Each MAC cycle is a frame of 3780 bits with dedicated time slots within the MAC cycle to send data bursts for uplinks and downlinks. The MAC cycle repeats at a 240 msec rate, providing the basic 15,750 bit/sec rate of the VDL Mode E waveform.

The ground station can transmit uplinks in its dedicated time slot without possibility of interference by any aircraft. An aircraft transmits downlink data messages in the downlink data time slot only after first requesting and receiving permission by the ground station. Permission is requested using a dedicated reservation request (RR) time slot assigned for each aircraft in the network. This architecture allows the ground station to manage and schedule the priority of downlink messages. It also prevents simultaneous downlink transmissions. This protocol insures that virtually every downlink message will be received correctly from aircraft on the network that is within range of the ground station.

Management Channels

As in the VDL Mode 3 system, Management (M) channels are used by the ground and aircraft for sub-network log-in/log-out, frequency handoffs, and other general net management functions. The downlink M channel is accessed on a random access basis by aircraft for these non-time critical functions.

The uplink M burst provides synchronization for the MAC cycle so that aircraft can properly determine timing for all downlink bursts. The uplink M channel also contains normal M channel net commands as well as responses to any reservation requests sent in the preceding MAC cycle. The uplink M channel contains a field for an ACK to any downlink message in the preceding MAC cycle.

Reservation Requests

A request-to-send and clear-to-send protocol is used for transmission of downlink message transmissions by aircraft in the downlink data burst. If a downlink transmission is required, an aircraft sends the request in its assigned RR (Reservation Request) burst. The ground station will grant permission for the downlink during the uplink M channel in the next MAC cycle. The downlink MAC cycle assigned may be later than the current MAC cycle, depending upon the message priority and other downlinks in the queue.

The RR bursts are accessed on a periodic basis by each aircraft in the sub-network. Each aircraft in the sub-network is assigned a specific RR burst in the epoch. An epoch is a series of MAC cycles and the number of MAC cycles in the epoch depends upon the maximum capacity of aircraft in the particular network. For a subnetwork with a capacity of 60 aircraft, the epoch is 6 MAC cycles (6 MAC cycles x 10 RR slots per MAC cycle). This assigned, deterministic method of polling guarantees 100% accessibility for a reservation request by an aircraft with a latency of no more than 1.44 seconds for a 60 aircraft sub-network (6 MAC cycles * 0.24 sec/MAC cycle).

Assignment of an aircraft to a specific time slot in the field of RR bursts in the epoch is made during the aircraft's initial log-in to the sub-network. Using the uplink and downlink M channels, the aircraft and ground exchange a series of log-in messages and as part of this exchange, the aircraft is assigned a unique local identification code of 8 bits. Each local ID is mapped to a RR burst time in the epoch with the current MAC cycle position in the epoch annunciated by a code in the M channel portion of the uplink burst.

Each aircraft in the sub-network will always transmit in its assigned RR slot, either with a reservation request for a specific number of downlink slots or a null request. The null request is used by the ground station to monitor continuing aircraft presence and signal strength. Distance measurement is also available from a measurement by the ground station of the time of arrival of the RR burst from the aircraft. This information may be useful by the ground network as part of the channel changing/hand-off procedures.

There is a dedicated RR time slot in each MAC cycle used to reduce the time required to transmit a reservation request for either urgent or emergency class messages. This urgent/emergency RR time slot is available for access every 240 msec on a random access basis by any aircraft logged into the sub-network. This definition of this time slot alternates between urgent or emergency request with either class message available every 480 msec. It may be used by any aircraft to expedite reservation requests for urgent or emergency messages without waiting up to 1.44 seconds for its dedicated RR burst.

Uplink Data

Uplink data is sent every MAC cycle and is appended to the symbols in the uplink M channel burst, so no separate synchronization data is needed for the uplink data. If the ground station has no uplink message to send to any aircraft, then the uplink data capability is used to send a broadcast type message with station ID and statistical or maintenance information.

The Uplink Data field is 576 bits (72 bytes). A 62,72 Reed Solomon forward error correcting (FEC) code is re-used from the VDL Mode 3 design and provides a very low block failure rate even when operating at the system's lowest bit error rate of 1×10^{-3}.

Since over 95% of CPDLC messages can be contained within a single Uplink Data burst [Appendix A], this provides a theoretical capacity of 250 messages per minute.

Downlink Data Burst

A Downlink Data burst opportunity occurs every MAC cycle and is accessed by an aircraft only if a reservation has been granted. The Downlink Data burst is also 72 bytes and uses the same 62, 72 FEC as the uplink.

Downlink ACK Burst

A burst at the end of each MAC cycle permits an aircraft to send an ACK to any uplink message that was directed to it in the current MAC cycle. The ACK burst time slot is about 160 msec after the end of the uplink message, providing time for the addressed aircraft to decode the uplink, perform the Reed Solomon decoding and verify the CRC of the message. This design approach permits a CPDLC uplink to be sent and ACKed in a single MAC cycle. If the uplink message requires several MAC cycles to send, the ACK is not expected by the ground until after the final MAC cycle in which the remaining portion of the message is transmitted.

Propagation Guard Time

All of the downlink bursts have a guard time at the end of bursts to accommodate propagation delays from aircraft operating as far as 265 nmi from the ground station.

Co-Channel Operation

Co-channel operation in the existing analog AM system requires large geographical separation between ground stations to prevent interference between different user groups. This is due to the possibility of air-to-air interference from high altitude aircraft where the line of sight (LOS) range can be of over 500 nmi.

Because a dedicated uplink time slot is used, no air-air interference scenario exists in the 2D configuration. This permits closer geographical spacing between ground stations than with the existing analog system. The digital characteristics of the VDL Mode E D8PSK waveform have been measured in prototype equipment and it requires only a 16 dB or better ratio in signal levels between desired and undesired uplink bursts to provide the required minimum bit error rate (BER) performance.

For aircraft as high as 50,000 feet, the line of sight (LOS) is about 275 nmi and beyond this distance, the signal strength of uplinks drops rapidly. If two co-channel ground stations are separated by 500 nmi, a high altitude aircraft at the edge of normal coverage (at 200 nmi) will be 300 nmi from the co-channel ground station. 300 nmi is well beyond LOS and the signal from the co-channel station will be attenuated below the 16 dB interference threshold and will permit achieving the minimum system BER during reception from the desired station.

The lower geographical separation requirement for the 2D configuration of VDL Mode E provides substantial frequency re-use opportunities. Figure 2 shows an example of the co-channel frequency reuse that is possible between four hypothetical 2D configuration ground stations in Europe. The solid lines around each of the ground stations represent true distance of the 275 nmi LOS for each station for aircraft at 50,000 feet.

Figure 2. Example of Co-Channel Frequency Allocations with VDL Mode E

Overview of a VDL Mode E Data Link Network

In a future Mode E CPDLC network, every IFR equipped airport will have at least one 2D configuration ground station. The physical location of the station on the airport insures coverage for aircraft in the ground or terminal domains. This single station can also serve aircraft in the high altitude en-route domain out to a range of at least 200 nautical miles, with range depending upon an aircraft's altitude and any obstructions from terrain.

More than one ground station will be required at airports where the peak traffic loading of ground and terminal domain traffic requires higher capacity. Each airport will also contain at least one backup station, as in the existing analog system. In addition to backup in case of failure of the primary station, these backup stations can also be used to provide temporary peak capacity by operating on frequencies not needed by other temporarily lightly loaded sectors. The addition or deletion of channels is transparent to the aircrew since the ground network automatically re-tunes the aircraft radio to new channels as required.

When properly sited, such a network will provide adequate data link capacity in a large region for any form of ATC communications. Because data link uses specific addressing for routing of messages, aircraft in all flight domains can share a given channel. Of course, if the most efficient channel capacity utilization is not required, individual ground stations can be allocated at each airport for specific domain traffic, such as a station dedicated only for en-route aircraft, tower communications, etc.

Channel Assignments

Once an aircraft is logged-on to a 2D channel, new channel assignments are very efficiently determined and commanded by the ground network since it has knowledge of the aircraft's current position (through ADS-B or radar/Mode S coverage) and flight plan as well as the loading on all other available 2D channels and their coverage areas.

The aircraft will operate on an assigned channel as long as the ground network projects that a reliable RF link is possible and periodic downlink RR responses from the aircraft confirm this in real-time. As an aircraft's 3D position changes such that a new channel is required, the ground network sends commands on the uplink M channel to re-tune the aircraft to a new data link channel. The frequency transfer can also be to a voice channel, either VDL Mode E or analog AM. A frequency change commanded by the ground station will occur well before the aircraft reaches the limits of the coverage area or begins any planned maneuver, such as descent, that will take it out of coverage. Should the RF link ever be lost for any unplanned reason, the aircraft radio will have the capability to automatically search and log-on to any 2D ground station that it can receive in its current location. Starting from that channel, the aircraft can then receive new frequency assignment commands from the ground network.

Capacity of a VDL Mode E System with 2D Configuration

The capacity of a 2D channel is set by the average and peak delays encountered in message deliveries. The Eurocontrol MACANDO document [3] specifies delays for transmission of various classes of messages. The shortest delay requirement is for emergency messages and is not more than 2 seconds (95% of messages must not exceed this limit). Tactical communications messages must be delivered within 5 seconds at 95% confidence level and 15 seconds at the 99.996% confidence level.

Latency for Emergency Messages

For both uplink and downlink emergency messages, an examination of the 2D structure confirms that the 2 second requirement can be satisfied. Any pending messages in the uplink queue can be cancelled by the ground station and replaced by an emergency message. Because an uplink can be sent at 240 msec intervals and ACKed by aircraft in the same MAC cycle, the 2 second requirement is easily achieved.

For emergency downlinks, requests to transmit can be sent in no more than 480 msec by use of random access on the Emergency RR channel. Because the ground station can cancel reservations for any pending downlinks and simultaneously grant the emergency downlink in the same MAC cycle, the latency for a single MAC cycle downlink emergency message is no more than 800 msec.

Latency for Tactical Uplink Messages

For tactical communications, a 5 second latency for 95% of messages applies. Studies have shown that CPDLC operations will require an average of 2 uplinks and 2 downlinks per aircraft over a 1 minute period, or about one transmission every 30 seconds[1] [4].

For uplink messages, there is a dedicated burst opportunity at the 240 msec MAC cycle rate. Since a very high percentage of CPDCL messages can be contained in one single downlink burst in a MAC cycle, this provides about 250 CPDLC uplinks per minute.

With 250 messages per minute, this is a capacity of 125 aircraft with no delays. However, this requires that all uplinks be evenly distributed over time and that CPDLC messages be contained in one uplink burst. In actual operation, when multiple messages simultaneously arrive for uplink transmission, they need to be placed in a transmit queue since only one uplink burst per 240 msec can be sent. In addition, some messages will be longer than can be conveyed in one MAC cycle (62 bytes of application data) and will require more than one MAC cycle for transmission of the entire message. Studies show that uplink messages will vary exponentially from 1 to 5 MAC cycles [5].

The limit on the size of the uplink queue is about 20 MAC cycles since this will take 4.8 seconds to transmit the last-in message in the queue and will just comply with the 5 second latency specification.

A simulation of the uplink was developed that contained N different message sources creating messages with sizes varying in an exponential manner between 1 and 5 MAC cycles. The time between messages to be transmitted by the uplink was randomly varied in a uniform distribution with an average of 30 seconds. It is recognized that some studies have suggested that tactical uplink message arrivals be modeled as exponential in nature with a longer (147 second) period [5]. However, for this initial examination of capacity, the uniform distribution with a period of 60 seconds (30 sec mean) was chosen and is actually a more demanding loading.

The queue at the beginning of the simulation was set to 20 MAC cycles so as to impose the worse case starting condition of about 5 seconds queue delay. The number of simulated aircraft was varied while monitoring peak delay and it was determined that the equivalent of 75 different aircraft could be serviced with uplinks with the highest peak delay at about 5 seconds.

This peak delay may more closely represent the 99.996% latency requirement (15 seconds) rather than the 5 second, 95% requirement, but for a very conservative estimate, an uplink capacity of 75 aircraft will be used. Figure 3 shows one output of the simulation over a 600 second period.

[1] This loading does not include air-air broadcasts for ADSB purposes. The 2D VDL Mode E configuration described is not intended for air-air data link applications. Other VDL Mode E configurations can provide this capability.

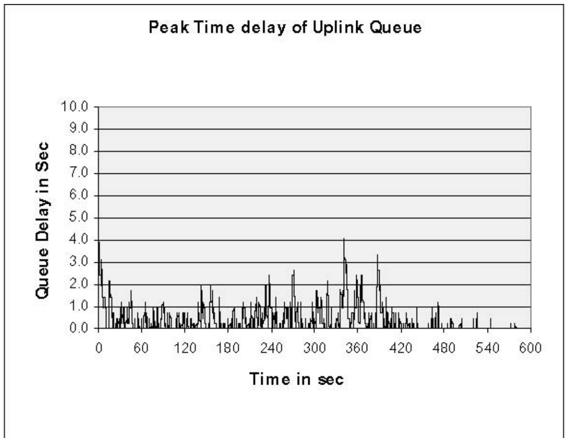

Figure 3. Example of Uplink Queue Delay

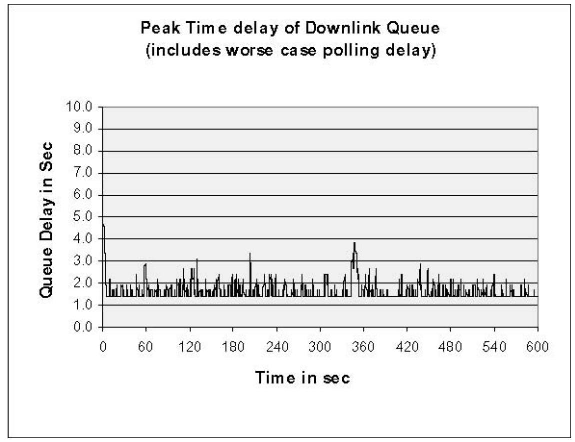

Figure 4. Example of Downlink Queue Delay

Latency for Tactical Downlink Messages

Transmission of a downlink message by an aircraft requires first sending an RR request in its assigned RR burst in a MAC cycle, receiving an assignment in the next MAC cycle, and then finally, transmitting the message in the assigned MAC cycle. The use of assigned RR channels for each aircraft guarantees reservation request access at no more than .024 * N sec, where N is the number of aircraft logged in to the subnetwork on the channel.

The downlink capacity will be lower than the uplink capacity since the worse case time to send a RR burst must be included in the total 5 second latency limitation. Using the same simulation tool and assumptions as for the uplink, it was determined that 60 aircraft could be serviced with the largest peak delay, including worse case polling time, of 5 seconds.

Figure 4 shows one output of the simulation over a 600 second period including the fixed delay of 1.44 seconds for polling with 60 aircraft. The downlink simulations were initialized with a queue of 15 MAC cycles to impose the worse case starting condition of 5 seconds.

Since the channel capacity is set by the smallest value obtained for either uplinks or downlinks, a working value of 60 aircraft per RF channel is used.

Peak Capacity of a 2D Network in Europe

In a future data link network, not all of the 8.33 kHz channels will be available for data link since some will need to be allocated for voice and other non-ATC applications. Assume that by the year 2050 there has been a near 100% transition to CPDLC data link for all IFR traffic and that a network exists that uses only 60% of the available 8.33 kHz channels. This allows 40% of the 8.33 kHz channels to be reserved for other non-data link applications such as IFR voice backup, AOC, and low altitude, restricted airspace VFR voice communications. With 1338 channels and a loading of 60 aircraft per channel, this provides 82,080 simultaneous CPDLC connections without any frequency re-use. As previously shown, frequency re-use is possible every 500 nmi providing a reuse factor of at least three in core European airspace. This enables 240,000 simultaneous two way air-ground CPDLC connections.

Recent statistics from Eurocontrol CFMU indicates the highest daily air traffic to date occurred in Europe on September 9, 2004 with 29,495 total IFR daily flights [6]. Estimates for traffic growth vary but average about 3.3% per year

[3]. A 3.3% per year growth in air traffic will result in 131,330 flights ***per day*** in the year 2050.

It should be recognized that the theoretical peak data link network capacity can not be fully utilized in actual operation since all ground stations in the system can not be simultaneously loaded to their maximum capacity. One example of a limitation is a ground station sited at low traffic count airfield. If the station's coverage is also outside most high altitude traffic routes, these stations may have less opportunities to receive assignments of high altitude traffic and will not operate at their maximum capacity.

Even if all forms of inefficiencies reduce total CPDLC network capacity as much as 50% (30 aircraft per ground station), there will still be available over 120,000 simultaneous CPDLC connections available. Table 1 summarizes the projected peak capacity of the VDL Mode E system in the VHF spectrum in the year 2050, including backup voice operations using the 2V VDL Mode E service. This instantaneous peak capacity of over 133,000 simultaneous aircraft can easily serve the projected daily traffic total of 131,330 flights in the year 2050.

Table 1. Estimate of Aircraft Communications Capacity in Europe in Year 2050 using VDL Mode E

Function	Allocation	Total circuits	Total channels with frequency reuse	Total active aircraft
Datalink	60%	1,338	4,014	120,420
Voice	40%	1784	2,676	133,800
			Peak capacity->	**133,800**

Notes:	
Total available 8.33 kHz channels	2230
Frequency Reuse Factor for data link channels	3
Frequency Reuse Factor for voice channels	1.5
Aircraft per data link channel	30
Aircraft per 2V voice channel (2 voice circuits per channel)	5

Conclusions

This paper has identified and discussed the proposed 2D data link configuration of the VDL Mode E system that can be used in a high integrity, high capacity, and low latency CPDLC network for VHF air traffic communications.

In combination with the 2V voice configuration of VDL Mode E, the system can be phased-in on 8.33 kHz channels to provide voice and data link capacity in excess of that forecast for air traffic through the year 2050.

References

[1] Phillips, Brent, 2004, "Future Communications Study", http://acast.grc.nasa.gov/workshop/2004/FAAEurocontrol_Future_C omm_Study /01-Phillips.pdf

[2] Studenberg, Fred, 2004, "A Digital TDMA System for VHF Aeronautical Communications on 8.33 kHz Channels", Presented at IEEE 23rd DASC, Salt Lake City

[3] Renaud, Philippe, July 2002 "Operating Concept of the Mobile Aviation Communication Infrastructure Supporting ATM beyond 2015, WP2 -Operating Concept for the Future Mobile Communication Infrastructure," D2 v1a, Brussels, Eurocontrol

[4] Kabaservice, Thomas, 2003, "Technical And Economic Benefits Of VHF Integrated Voice and Data Link For Air Traffic Control", White Paper from Harris Corporation, Page 2

[5] MITRE/CAASD, 1996, "A Proposed VDLT ATS Traffic Model for Two-Way Data Link Applications Capacity Simulation"

[6] Eurocontrol – CFMU, 2004, "AFTM Summary 2003", www.cfmu.eurocontrol.int/...cs/index.htm

Appendix A – Examples of Message Sizes for Simple and Complex CPDLC Messages

Examples of simple and complex CPDLC messages

SIMPLE = WILCO = 40 bytes

14:35:43 (AVLC) TX 0x5101c0a INFO
(P=0) N(s)=0 N(r)=7
001645 Frame Data:
001646 16 02 1c 50 b0 ec 1e 1b e0 1b ff c4 1b 28 f6 41
001647 00 12 08 f0 00 34 82 c3 02 64 28 00 a5 47 84 10 84 c3 a3 a8 20 04 c8 fa

COMPLEX = um120+um135 = 55 bytes

- allDisMsgStr=MONITOR EDYY MAASTRICHT CENTER 129.000 MHZ, CONFIRM ASSIGNED LEVEL

14:34:54 (AVLC) RX 0x5101c0a INFO
(P=0) N(s)=4 N(r)=6
001528 Frame Data:
001529 b2 ec 1e 1a 14 02 1c 51 c8 1b ff 08 1b 1d d6 41
001530 00 35 08 f0 02 02 81 c3 02 c5 dc 00 a8 0c 13 42
001531 10 98 74 5b 04 f1 11 62 59 b2 f3 60 c1 a7 52 94
001532 98 72 2a 01 89 84 38

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