L-band Compatibility of LDACS1

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Abstract

In order to cope with the increasing demand of communication capacity in the aeronautical sector, the Future Communications Infrastructure has been developed. For air ground communications currently two candidates are considered for the L-band digital aeronautical communication system LDACS. Both L-band systems use frequency bands assigned to both civil and military navigation systems. Hereby of special interest is the distance measurement equipment due to its wide and extensive use in civil aviation. Prior to the deployment of any of the candidates, the compatibility towards those legacy systems has to be confirmed. This paper presents the result obtained during compatibility measurements of LDACS1 carried out at labs of the German Air Navigation Service Provider, DFS Deutsche Flugsicherung GmbH, in March and September 2011. The paper deals with the interference on an airborne DME caused by LDACS1 emissions.

1 Introduction

To enable the modernization of Air-Traffic Management (ATM) as currently pursued by NextGen [1] in the US and SESAR, Single European Sky ATM Research in Europe [2], new and efficient communication, navigation and surveillance technologies are required. For communications, a common understanding within ICAO has been reached that a single data link technology is not capable of covering the communication needs for all phases of flight. Therefore, the Future Communications Infrastructure (FCI) has been developed comprising a set of data link technologies for aeronautical communications [3]. For the airport, AeroMACS (Aeronautical Mobile Airport Communications System) is currently developed within NextGen and SESAR which is strongly based on the WiMAX standard. ESA initiated the development of a future satellite-based communications system for aviation within their ESA Iris program, supplemented by work performed within SESAR. For air/ground communications, currently two L-band Digital Aeronautical Communication System (LDACS) options were identified. LDACS1 option employs a frequency division duplex (FDD) broadband transmission using Orthogonal Frequency-Division Multiplexing (OFDM) [4]. LDACS2 option is a single-carrier system employing time-division duplex (TDD) [5]. In order to provide the final LDACS selection, the radiofrequency compatibility between LDACS and the legacy L-band systems should be proved. The Distance Measuring Equipment (DME) operating as FDD system on a 1 MHz channel grid is the major user of the L-band and its sensitivity to LDACS interference is the prioritized test scenario [6]. Whereas LDACS2 is expected to operate in the DME free frequency band between 960-975 MHz, LDACS1 additionally offers the opportunity to use spectral gaps between existing DME channels, thus increasing the potential number of communication channels. This inlay deployment option for LDACS1 is the most interesting but also the most critical case regarding its interference on DME as well as the interference from DME on LDACS1.

Current work on LDACS, performed under the framework of SESAR within the corresponding SESAR project P15.2.4 "Future Mobile Data Link System Definition", aims to set the evaluation criteria for L-band compatibility testing, to define the measurement set-up for LDACS evaluation, and develop laboratory prototypes to be used in the compatibility tests. Early tasks of the P15.2.4 project produced documents that summarize different interference scenarios and the coexistence criteria. The interference cases where LDACS transmitter (TX) acts as interference source are covered by [7] and the cases where LDACS receiver (RX) is a victim system are reported in [8]. The interfering as well es the victim system can be a ground station (GS) or an airborne station (AS), where different constellations result in different distance ranges between the two systems.
Parallel to the initial SESAR activities, DLR has implemented an LDACS1 physical layer laboratory demonstrator in FPGA technology based on the current LDACS1 specification [4]. The demonstrator enables investigations of both the influence of the LDASC1 waveform on the legacy L-band systems and the interference of the legacy L-band systems on the LDACS1 receiver. Independently from the SESAR activities, DLR in cooperation with the German air navigation service provider Deutsche Flugsicherung GmbH (DFS) started to perform a set of preliminary interference measurements. These test measurements have the goal to assess the sharing conditions between LDACS1 and DME in terms of acceptable levels of the interfering signal as a function of the frequency separation. The first conducted test measurements reported in this paper comprise only an interfering LDACS1 ground or airborne transmitter and a victim airborne DME receiver. The following section describes the interference scenarios relevant for these constellations. The compatibility criteria for DME are explained in Section 3 and Section 4 describes the spectral properties of the LDACS1 signal. Section 5 presents the results obtained in the measurements. A preliminary conclusion on sharing conditions between DME and LDACS1 is given in Section 6.

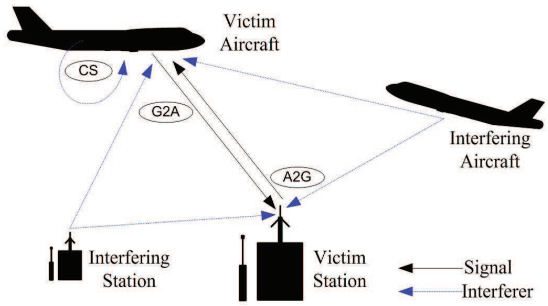

Figure 1: Interference scenarios

2 Interference Scenarios

Fig. 1 shows all theoretically possible interference scenarios between DME and LDACS1 and Fig. 2 the envisaged spectrum allocation of LDACS1 in the inlay deployment option and the DME channel assignment. The relevant cases where LDACS TX acts as interference source are summarized in [7]. However, considering possible deployment scenarios, distances between the interfering and the victim system, as well as the frequency channel usages, the following three scenarios are identified as the most relevant for LDACS1 [6]:

a) LDACS1 GS TX - DME AS RX (G2A)

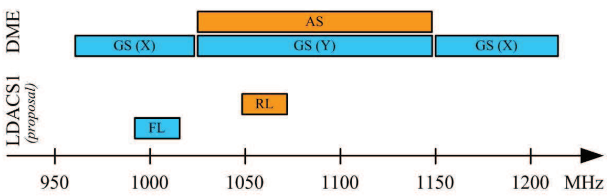

Figure 2: Frequency allocation of DME and LDACS1 in inlay deployment

b) LDACS1 AS TX - DME AS RX (Co-site)

c) LDACS1 AS TX - DME GS RX (A2G)

Case a) represents the situation where signals transmitted by the LDACS1 ground station are being received by an airborne DME station. The closest distance between involved systems is assumed to be as low as 50 m, resulting in a path loss between antennas of 66 dB [7]. The estimated maximum distance in this scenario of 200 nautical miles results in a free space path loss between antennas of approximately 144 dB. LDCAS1 GS transmits continuously with a frequency spacing of $\Delta f = k \cdot 500$ kHz, $k = 1, 2, ...$, from the victim DME system.

Case b) represents the situation where LDACS1 signals transmitted by an aircraft are being received by the DME device installed on the same aircraft. The isolation between two airborne systems on the same aircraft is estimated to 30 dB [7]. DME GS can transmit on any DME channel between 960 and 1213 MHz and hence, any frequency separation between LDACS1 AS TX and victim DME system in multiples of 500 kHz is possible, including co-channel transmission. In general, the victim airborne DME receiver could be influenced by the blocking/desensitisation caused by the strong "in-band" part of the airborne LDACS1 TX signal and its out-of-band products. The performance will then depend upon the selectivity of the DME receiver. Besides, in case of a large frequency spacing between two systems, the radiated LDACS1 TX broadband noise may influence the DME reception. In both cases, the interference impact will also depend on the duty-cycle in the LDACS1 reverse link transmission (see Chapter 4).

Case c) represents the situation where LDACS1 emissions from an airborne aircraft are being received by a DME ground station. Thus, the conditions are similar to case a) with the difference that LDACS1 transmissions are not continuous and therefore, beside frequency spacing, the duty cycle is also a variable test parameter. Due to the current lack of a DME ground station, test case c) could not be measured yet.

3 DME

DME interrogators onboard an aircraft provide the slant range distance between the aircraft and the replying DME transponders on the ground. The slant range distance is measured via determination of the signal traveling time between aircraft, ground and and back to the aircraft. For this purpose the DME interrogator transmits pairs of Gaussian pulses with a defined spacing and the ground transponder replies with another pair of pulses after a determined period of time. During the search mode the maximum allowed repetition rate is 150 pulse pairs per second (ppps) [9]. The aircraft interrogator correlates the replies with the pulses to distinguish, which ones are in response to its own interrogations. This acquisition process should be completed in less than 2 seconds. Once the interrogator obtains lock to the GS, it enters the track mode where the repetition rate is reduced to about 30 ppps.
Typically, the DME devices in use provide much less than the specified maximum number of pulse pairs in the search and the tracking mode. Besides, different DME devices have also different signal processings including filter characteristics and hence show different performance and susceptibility to interference.

The maximum number of pulse pairs transmitted by a DME ground transponder is 2700 ppps in the constant mode. However, some are able to operate with a squitter rate of 3600 ppps under peak traffic conditions. The ground TX operating power is 63 dBm. On the airborne side, the TX power is variable depending of the type of equipment and the maximal possible power setting is 63 dBm. For laboratory test purposes, the ground transponder was replaced by the DME Ground Station simulator JCAir SDX 2000 with the reply frequency set to 2700 ppps.

A general criteria for testing DME ground transponder receiver is the Beacon Reply Efficiency (BRE). BRE represents the ratio of the number of sent pulse pairs to the number of received interrogation pulse pairs. Interference will lower the amount of interrogations which are successfully detected and therefore reduce the BRE. However, only the JCAir SDX 2000 as ground station simulator was available up to now, which is an inappropriate ground station under test. Therefore, the interference tests have not been performed yet for this scenario.

According to the compatibility criteria proposed in [7] for the DME airborne receiving equipment in the presence of undesired interference, the compatibility tests for DME comprises recording of the following values:

- TTA (Time To Acquire)
- ASOP (Acquire Stable Operating Point)
- BSOP (Break Stable Operating Point)

TTA is defined as the time an interrogator needs to acquire a stable track when the desired signal level is set to the minimum specified value. In [10], a TTA of around 50 s is required for DME devices. When evaluating the impact of UAT on DME in [11], the interference is considered tolerable, when TTA measured with interference present at a reference signal level, $\nu_{TTAwithI}$, fulfills

$$\nu_{TTAwithI} \leq max(\nu_{TTA} + 0.5s, \tilde{\nu}_{TTA})$$

$$\text{with } \tilde{\nu}_{TTA} = \nu_{TTA} + 2 \cdot \sigma_{TTA},$$

where ν_{TTA} is the mean value of TTA in seconds without interference at the reference signal level, and σ_{TTA} is the standard deviation of TTA in seconds without interference at the reference signal level.

Controversially, this value can be less than 2 s which is the upper limit for DME acquisition performance defined by [12]. After obtaining the TTA values for different desired (D) and undesired (U) signal levels, ASOP is defined as the D/U point at which the DME interrogator is able to acquire a stable track (stable within 2 minutes observation time with a tolerable TTA value). BSOP is defined as the D/U point at which the DME interrogator loses the track.

Two different Devices Under Test (DUTs) have been used in the measurements: Rockwell Collins DME900 is an interrogator typically used in air transportation and Bendix/King KDM706A is a device used in general aviation. Whereas the signal processing in DME900 is partly digitalized, KDM706A is an entirely analog device. Table 1 shows the relevant parameters of these two devices.

Table 1: Used airborne DME equipment

DUT	DME900	KDM706A
search mode [ppps]	18	100
track mode [ppps]	2	25
min. D [dBm] ([9])	-82	-82
measured $\tilde{\nu}_{TTA}$ [s]	1.6	2.5

4 LDACS1

In the air-ground operation mode, LDACS1 employs OFDM in the forward link (FL) transmissions from GS to AS and a combined Orthogonal Frequency- / Time- Division Multiple Access (OFDMA/TDMA) in the reverse link (RL) from AS to GS. FL and RL are on separated frequency channels with an envisaged frequency spacing of 63 MHz which should enable the frequency planning to be coupled with the DME frequencies. In the inlay deployment of LDACS1, a 500 kHz LDACS1 channel is located in the middle between two DME channels.

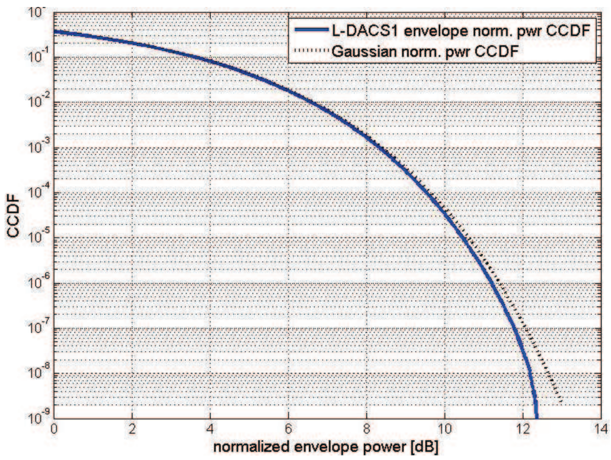

Figure 3: LDACS1 TX power per sample without PA

Due to its broadcast nature, the FL employs a time continuous transmission received by all

AS. As the maximum transmit power of a GS, currently 41 dBm are considered. This power refers to the average OFDM signal power. The peaks of the signal may be theoretically up to 17 dB higher due to the OFDM's Peak to Average Power Ratio (PAPR). In a practical implementation, however, the PAPR is most likely to be limited to a lower value. The hardware realization of the LDACS1 demonstrator used in the measurements limits the PAPR to 12.4 dB. Fig. 3 presents the Complementary Cumulative Density Function (CCDF) of the signal power for each sample, normalized by the average transmission power, thus indicating a low frequency of the occurrence of high PAPR values in the transmitted signal.

RL dynamically allocates a half of or the whole effective bandwidth of 498.05 kHz for a certain time to an AS. Hence, the RL transmission is not continuous and the percentage of time per second in which an aircraft is transmitting is given by duty cycle (DC). The duration of the continuous transmission of an aircraft can vary between $T_{min}^{\mathrm{RL}-active} = 0.6$ μs and $T_{max}^{\mathrm{RL}-active} = 56.88$ ms. In general, the maximum DC can be limited by the resource allocation algorithm. Actually, the highest acceptable DC resulting from the final measurements should be considered by the resource allocation provided by the LDACS1 Media Access Control (MAC). For the average transmit power currently 42 dBm are planned.

The DLR LDACS1 prototype consists of the LDACS1 TX/RX prototype implemented on a Parsec FPGA system and Bögl & Partners Systemtechnik 10.7 MHz to L-Band RF frontend. The baseband demonstrator comprises the TX and the RX physical layer. The TX physical layer including adaptive coding and modulation as well as the complete framing structure for FL and RL is entirely realized in FPGA. The receiver for LDACS1 is not defined in the specification. For that reason and for being able to rapidly implement improved receiver algorithms, the LDACS1 receiver is implemented mainly in software. Only sampling and digital down-conversion from an intermediate frequency to baseband followed by fast data storage of the received baseband samples are implemented in FPGA. The stored signal is processed offline using a software receiver realizing all necessary receiving functions. In order to consider

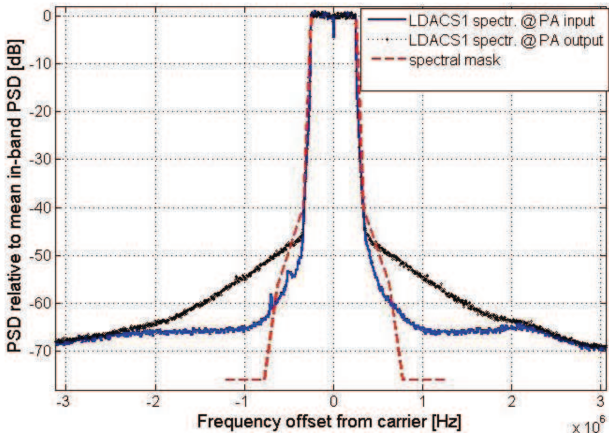

Figure 4: LDACS1 spectrum

the effects of signal amplification, the wideband Power Amplifier (PA) BLMA 0525-35 was used in the measurements to amplify the LDACS1 Tx signal to 35 dBm. The effects of the PA onto the LDACS1 spectrum are presented in Fig. 4.

5 Measurements and Results

To measure the interference caused by an LDACS1 transmitter on the interrogation process of a DME, the interferer is inserted between ground and airborne station as shown in Fig. 5. Two circulators are used to decouple the two paths between the ground and the airborne DME and a coupler to superimpose the victim system with the interfering signal. The power level of the interferer can be adjusted using a step attenuator, while the power level of the desired signal at the victim receiver is kept constant at $D = -82$ dBm. Thus, the attenuator substitutes the propagation loss or the isolation between LDACS1 TX and DME RX.
The undesired signal level U of the LDACS1 interference and desired DME signal level D at DME victim receiver, both measured at the input of the victim DME system, are set into relation in the measurement. Thus, the compatibility criteria are evaluated in terms of desired-to-undesired power ratio D/U.

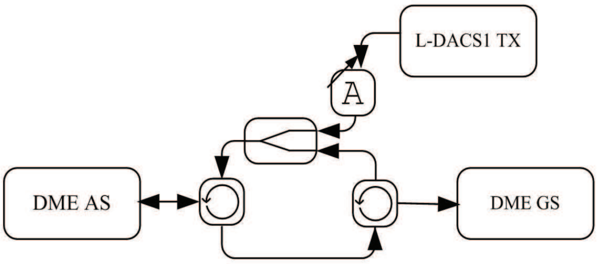

Figure 5: Measurement setup

As a core parameter, TTA has been measured for each undesired signal level U under consideration. Measurements started with a low value of U compared to the desired signal level D. Then U was increased until an D/U point was reached for which no acquisition has been achieved within 20 s. For each of the considered D/U value, mean TTA and standard deviation of TTA have been evaluated from 20 measurements. Whether the interference conditions are acceptable depends on the maximum TTA tolerable. Different tolerance values of TTA are regarded. One possible tolerance margin is the mean value of TTA plus two times the standard deviation of TTA without interference. This rule yields the target TTA values of 1.6 s for DME900 and 2.5 s for KDM706A, according to Table 1. Additionally, maximum TTA of 2 and 5 s are also chosen as possible target values.

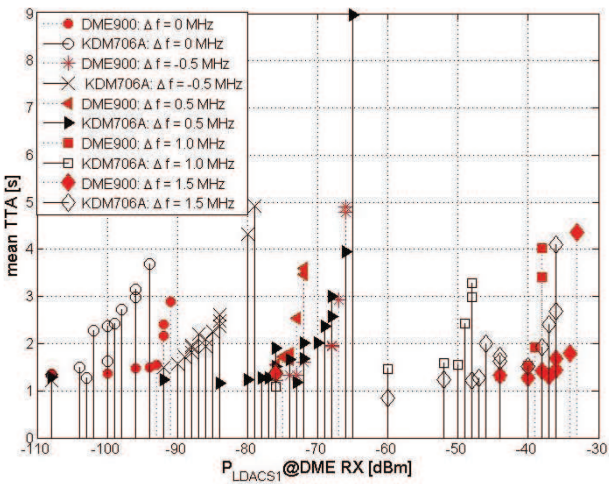

Figure 6: TTA versus LDACS1 power U for $D = -82$ dBm and different frequency offsets.

5.1 G2A Interference Scenario

For the interference scenario a) LDACS GS TX - DME AS RX, the DME frequency was set to 1004 MHz and the LDACS1 frequency was varied from 1002.5 to 1004.5 MHz in steps of 500 kHz. Fig. 6 shows the measured mean TTA values for different U, $D = -82$ dBm and different frequency spacings between the two systems. Noticeable is the different performance of DME900 and KDM706A. The high class Rockwell Collins device is less susceptible to LDACS1 interference. Moreover, due to a non-symmetric spectrum of the devices used, the impact of the undesired signal in not necessary the same on the adjacent channels on both side of the victim DUT. Furthermore, Fig. 7 compares the results of the measurements with DME900 with and without LDACS1 TX power amplifier. Obviously, PA increases the noise floor outside the DME channel and slightly impair the performance at frequency spacings above 1.0 MHz.

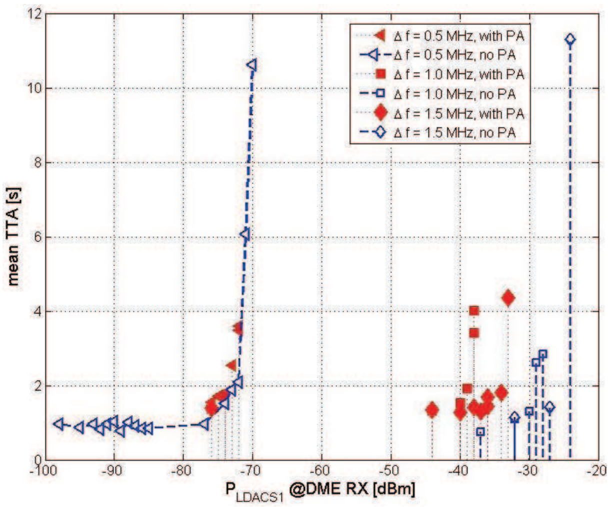

Figure 7: TTA versus LDACS1 power U for $D = -82$ dBm and different frequency offsets measured with DME900 with and without LDACS1 power amplifier.

The lowest D/U for which the mean TTA does not exceed the target value are summarized for different tolerance values for TTA assumed and different frequency spacings Δf in Table 2 for DME900 and in Table 3 for KDM706A.

Table 2: Acceptable D/U [dB] at DME RX for different TTA target values for DME900

TTA [s]	**1.6**	2	2.5	5
$\Delta f = 0$ **MHz**	**11**	11	10	9
$\Delta f = -0.5$ **MHz**	**-9**	-14	-14	-16
$\Delta f = +0.5$ **MHz**	**-6**	-8	-8	-10
$\Delta f = 1.0$ **MHz**	**-42**	-43	-43	-44
$\Delta f = 1.5$ **MHz**	**-45**	-48	-48	-49

Table 3: Acceptable D/U [dB] at DME RX for different TTA target values for KDM706A

TTA [s]	1.6	2	**2.5**	5
$\Delta f = 0$ **MHz**	21	21	**17**	12
$\Delta f = -0.5$ **MHz**	8	6	**3**	-3
$\Delta f = +0.5$ **MHz**	-5	-9	**-13**	-16
$\Delta f = 1.0$ **MHz**	-32	-23	**-33**	-34
$\Delta f = 1.5$ **MHz**	-35	-44	**-45**	-46

5.2 Co-site Interference Scenario

For the interference scenario b) LDACS AS TX - DME AS RX, the DME frequency was set to 1060 MHz. The impact of LDACS1 interference for different duty cycles was measured in co-channel case (LDCAS1 frequency set to 1060 MHz) and on the adjacent channel (LDCAS1 frequency set to 1059.5 MHz) with DME900. Generally, co-site interference is the worst case scenario as the undesired LDACS1 emission from the airborne TX at the airborne DME Rx can be as high as 11 dBm, whereas the desired DME signal as low as -81 dBm. The co-channel case and in general a small frequency separation between two systems in this scenario is theoretically possible, but can be avoided by an appropriate frequency planing. Nevertheless, even in case of large frequency separation, the out-of-band noise could already block the reception of the DME interrogator. However, a low duty cycle of LDACS1 transmission is expected to diminish the impact on the DME performance. In the test set-up, there was no possibility to switch off the PA emission simultaneously with LDACS1 TX transmission. Hence, amplifying LDACS1 signal to 11 dBm would result in a very high noise level of the PA which already blocks the DME unit also when there is no LDACS1 transmission. For this reason, the

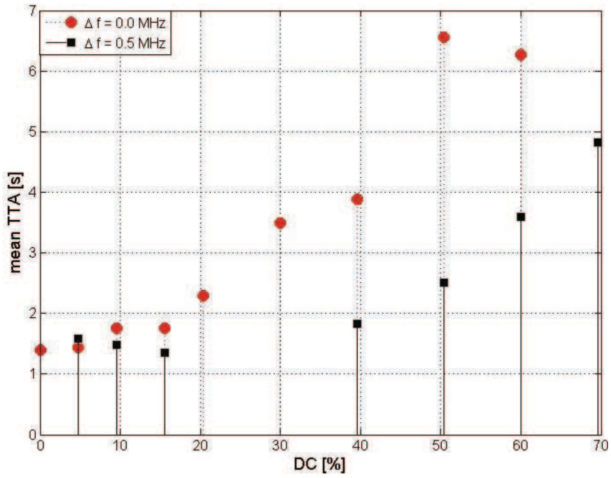

Figure 8: TTA versus DC for different frequency offsets measured with DME900.

Table 4: Acceptable DC[%] of LDACS1 airborne emission for different TTA target values for DME900

TTA [s]	**1.885**	**2.5**	**5**
$\Delta f = 0$ **MHz**	**15.6**	**20.4**	**40**
$\Delta f = 0.5$ **MHz**	**15.6**	**40**	**70**

LDACS1 TX power at PA output is chosen to be $U = -36.5$ dBm. This value is determined in the way to have a mean TTA value if LDACS1 TX is idle similar to the interference free case. The DME power level at the receiver is kept constant at $D = -82$ dBm. With this measurement settings, the no-interference case (DC= 0%) yield a new $\tilde{\nu}_{TTA}$ of 1.8854 s. Fig. 8 shows the measured mean TTA values for different DC settings and Table 4 summarizes the results stating the acceptable DC for different TTA target values.

6 Results Analysis and Conclusions

In general, when interpreting the measurement results, possible deployment scenarios should be taken into account. In ground to air communication, the distance is the major parameter. Considering for example that LDACS1 and DME ground stations are close, i.e. their distances to the airborne DME receiver are approximately the same, the expected D/U is around 22 dB. Besides, the analysis of the results obtained with the two DUTs, should be done regarding their performance in interference-free case. Results presented in Fig. 6 and Table 2 show that a D/U of -9 dB with LDACS1 interferer in an adjacent channel would not retard the acquisition process for DME900 when considering $\tilde{\nu}_{TTA}$ from Table 1. This TTA target is for DME900 the most stringent TTA requirement. Even 3 dB D/U required for KDM706A in an adjacent channel, regarding a target TTA of 2.5 s, are complied in adequate deployment scenarios. Tolerating TTA of 5 s allows for higher interference than desired power levels. Having an interfering signal with 1.0 MHz separation allows for undesired signal level to be 42 dB for DME900 and of 33 dB for KDM706A above the desired DME power level at the victim receiver.

Regarding the results in the co-site scenario, presented in Fig. 8 and Table 4, the most stringent TTA requirement allows for a DC of at least 15.6%. The next higher DC used in the measurement is 20.4%, hence, it can be expected that the actual DC margin is between these two values.

The results presented show that the LDACS1 co-existence with DME in the most strict inlay deployment option is feasible regarding the presented scenarios. However, the results should be confirmed with additional DUTs and the compatibility should be proved also for other interference scenarios. Furthermore, LDACS1 susceptibility to DME interference should be also tested.

The preliminary work presented in this paper is performed outside the SESAR project. These results will however be available for consideration when performing further tests within SESAR activities.

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