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. 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 the 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 in March and August, 2011. Both results for interference on the DME caused by LDACS1 and vice versa are dealt with.

Introduction

To enable the modernization of Air-Traffic Management (ATM) as currently pursued by NextGen [1] in the US and SESAR 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 candidate systems are under consideration for the L-band Digital Aeronautical Communication System (LDACS). LDACS1 employs a frequency division duplex (FDD) broadband transmission using Orthogonal Frequency-Division Multiplexing (OFDM). In contrast to that, LDACS2 is a narrowband single-carrier system employing time-division duplex (TDD). A major criterion for the final LDACS selection is whether the candidate systems can coexist with the existing legacy L-band system. Therefore, laboratory prototype testing of LDACS with respect to L-band compatibility is mandatory.

Current work on LDACS is performed under the framework of SESAR within the corresponding SESAR project P15.2.4 „Future Mobile Data Link System Definition“. In this project, evaluation criteria for L-band compatibility testing, the measurement set-up for LDACS evaluation, and laboratory prototypes are developed for performing the final LDACS selection. Besides the SESAR activities, DLR has already implemented an LDACS1 physical layer laboratory demonstrator in FPGA technology [6] based on the current LDACS1 specification [4,5]. 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. Thus, this LDACS1 physical layer laboratory demonstrator is capable of performing the required compatibility testing in L-band.

Therefore, in March and August 2011 the DLR in cooperation with the German air navigation service provider Deutsche Flugsicherung GmbH (DFS) conducted a series of measurements on that topic. The measurements were carried out for the different modes of both DME and LDACS1.

LDACS1 Overview

To allow a better understanding of the measurements performed a brief summary about the fundamental parameters of LDACS1 is necessary. For further details on LDACS1 refer to [5]. LDACS1 knows two different modes of operation, an air-ground (A/G) and an air-air (A/A) mode. However the A/A mode has not been specified yet, therefore this paper focuses on the A/G mode as specified in [5].

LDACS1 is a cellular system based on a network of ground stations (GS). The communication between a GS and an aircraft, here referred to as airborne station (AS), employs OFDM. Two different modes exist; the forward link (FL) incorporates transmissions from the GS to the AS while the reverse link (RL) is employed in the opposite direction. Both directions are separated by FDD. Due to its broadcast like nature the FL employs a time continuous transmission received by all AS. The different GS are separated in the frequency domain. As the maximum transmit power of the FL, currently 12.6 W (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 something below that value. In the RL a combined orthogonal frequency - / time division multiple access (TDMA) approach is employed, dynamically allocating certain blocks of subcarriers for a certain time to an AS. For the average transmit power currently 15.8 W (42 dBm) are planned. Both transmission modes use frequencies in the L-band and are separated in frequency direction by a spacing of 63 MHz. For the FL the frequency band from 985.5 to 1008.5 MHz is currently considered while the RL is to use the band from 1048.5 to 1071.5 MHz. Currently, within these frequency bands, an in-lay deployment of LDACS1 is considered. That means, a 500 kHz LDACS1 channel is located in the middle between to DME channels.

The nominal size of the fast Fourier transform (FFT) is 64. Using a subcarrier spacing of $\Delta f_s \approx 9.8$ kHz this leads to a nominal bandwidth of 500 kHz. However, only 50 subcarriers are applied to data transmission and 14 are left empty – 7 guard carriers on the left, six guard carriers on the right side, and the DC carrier. This leads to an effective bandwidth of $\Delta f_{useful} \approx 498.05$ kHz.

In Figure 1 the composition of an OFDM symbol in the time domain is shown. Each OFDM symbol with the useful symbol duration of $t_{useful} = 102.4$ µs (64 samples) is extended into a cyclic prefix of length $t_{cp} = 4.8$ µs (3 samples). Additionally a raised cosine windowing function is applied to each OFDM symbol reducing its out-of-band radiation. This adds another $t_{win} = 12.8$ µs (8 samples) on each side of an OFDM symbol. However, due to the overlapping of the windowing function between the consecutive symbols the overall signal duration is $t_{symbol} = 120$ µs (75 samples). The overall CP and windowing overhead is about 15 %.

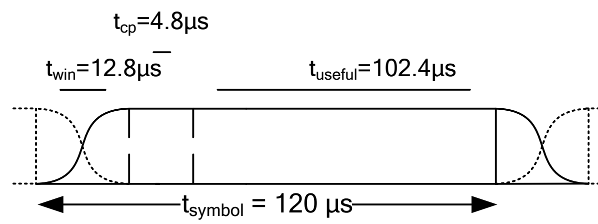

Figure 1. LDACS1 OFDM Symbol in the Time Domain

As for any modern communication system a vast number of different combinations of coding and modulation settings exist. Using those the transmission can continuously adapt to the current channel and interference conditions as well as user requirements. The coding consists of a Reed-Solomon (RS) code concatenated with a convolutional coding scheme. The overall coding rate can be varied. As modulation alphabets QPSK, 16QAM and 64QAM are available.

LDACS1 Framing

In the time continuous transmission of the FL different frame types are employed. Each frame type serves a certain purpose, e.g. transmission of general data, data for a specific user or control information. As an example one FL frame type is shown in Figure 2. The figure shows the time-frequency grid of an FL data/CC frame. This is a general frame type either used for the transmission of common control (CC) information or payload data. Two OFDM symbols reserved for synchronization are followed by a predefined number of data symbols. The pilots are scattered over the entire time frequency space in an irregular pattern. This pattern exhibits advantages compared to a regular pattern, where a pulse shaped interferer, e.g. DME, can destroy a large number of pilots at once leading to a degraded channel estimation which in turn might lead to an increased bit error rate (BER).

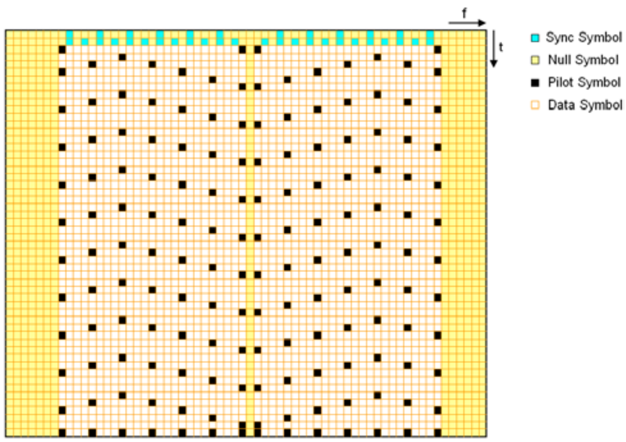

Figure 2. LDACS1 FL/CC Frame

As stated above, the RL is not a time continuous transmission but rather has to allow a random access ability. Therefore, periodically an opportunity exists, in which each AS may request resources for a RL transmission. This is done using the frame type shown in Figure 3. The RL random access frame shares strong similarities to a FL frame, however an AGC symbol is added to allow a correct adjustment of the receive amplifier. Additionally, the number of used carriers is reduced to 42.

The payload data of the AS is transmitted using frames of the types shown in Figure 4. A transmission contains of a header consisting of an AGC preamble and 5 synchronization symbols. The data symbols are transmitted in tiles consisting of 25 carriers in 6 OFDM symbols. The tiles are dynamically assigned to the different AS according to their requirements. To allow a reduction of the PAPR in the RL, additionally PAPR reduction symbols are transmitted, which are discarded at the receiver.

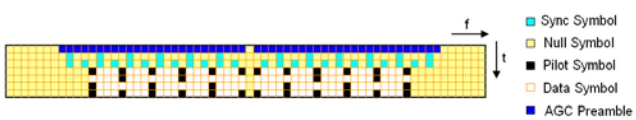

Figure 3. LDACS1 Random Access Frame

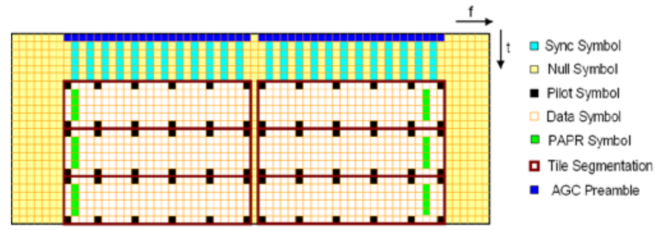

Figure 4. LDACS1 RL Frame Structure

The different LDACS1 frames are organized in a structure of super-frames shown in Figure 5 of a length of 240 ms. A super-frame consists of 4 multi-frames, a part reserved for broadcasting in the FL, and two random access possibilities for the different AS in the RL. The structure of a multi-frame is shown in Figure 6. The abbreviations DC and CC stand for dedicated and common control information, respectively. In the FL a multi-frame consists of data/CC frames, while in the RL the tile structure can be clearly observed.

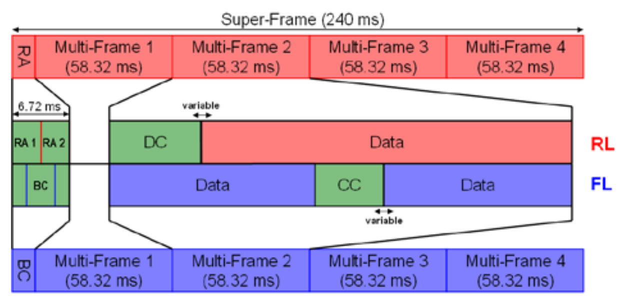

Figure 5. Super-frame Structure of LDACS1

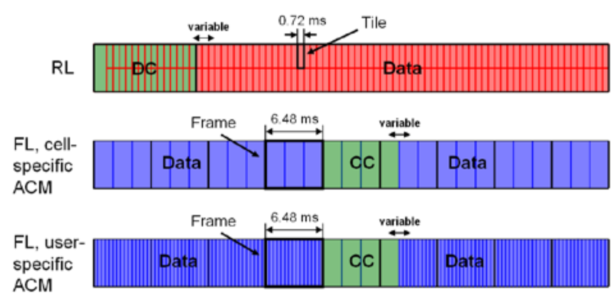

Figure 6. Multi-frame Structure of LDACS1

DME Overview

Knowledge of the fundamental ways of operation of a DME is necessary in order to evaluate the results of the measurements. For further details on that topic, please refer to [7]. The fundamental principles of a DME were developed in 1949 and have been used in civil aviation as navigation aid since the middle of the 1950s. The range of operation of a today's device is up to 200 nautical miles and it can serve a maximum of around 100 aircraft.

A DME system consists of two classes of devices. An airborne device (AS), the interrogator, and a ground station (GS) acting as transponder. With this set-up the distance between the AS and the GS, of which the position is known, can be obtained. A DME is usually coupled with a VOR device [7], which then allows, together with using knowledge about the altitude, the determination of the current position of the AS.

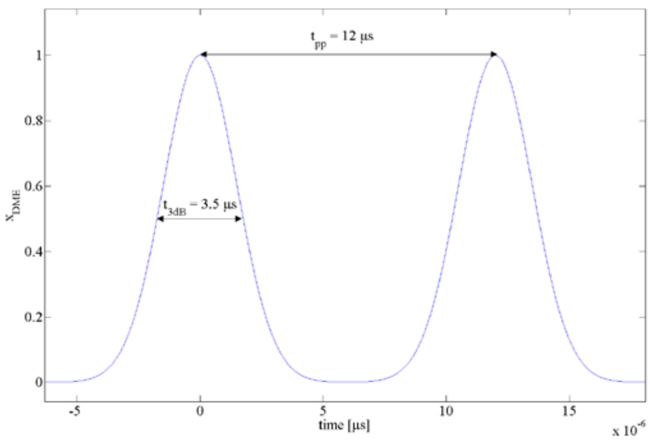

Figure 7. DME Pulse Pair

The interrogator works in the frequency bands 1025 to 1150 MHz and continuously sends Gaussian shaped pulse pairs, shown in Figure 7, to the interrogator with a certain rate. The reason to prefer pulse pairs over pulses is to avoid interference, e.g. by atmospheric effects. Two different modes for a DME device are considered: X- and Y-mode. They slightly differ in terms of transmission parameters used. For the X-mode the time between the two pulse pairs is t_{pp} = 12 µs (36 µs for Y-mode). The main advantage of choosing a Gaussian pulse is its limited out-of-band radiation. The maximum transmit power of the airborne device is limited to 1.25 kW (71 dBm). The interrogator responds using pulse pairs in either the band 962-1024 MHz / 1151-1213 MHz (X-mode) or in 1025-1150 MHz (Y-mode). The transponder does not answer immediately after a pulse pair has been received but rather waits a certain pre-defined dead time. This dead time avoids errors due to multipath reflections in the vicinity of the transponder. The transmit power of the ground station is limited to 15 kW (82 dBm). Since the bands are spaced in a 1 MHz frequency grid, an overall number of 126 frequencies pairs, each separated by 63 MHz, and 252 DME channels exist. To allow identification of the ground station, every 37 seconds the transponder stops its replies and transmits an identification sequence lasting 3 seconds.

The range of an AS to the GS, the slant range, is calculated by using knowledge about the radio propagation speed in air and the dead time at the transponder. If an aircraft has just entered the area of operation of a DME and it has no connection to any ground station yet, it is in search mode trying to acquire a distance lock on a transponder. In that state it usually transmits pulse pairs at a rate of a maximum of 150 pulse pairs per second (PPPS). After a lock on a DME station has been obtained, the rate is reduced to a maximum of 30 PPPS. Modern DME devices use a smaller amount of PPPS than the maximum number defined in the standard. This allows a ground station to serve more aircraft due to fewer collisions between the interrogation requests occurring. To allow a device to recognize whether a transponder's reply is intended for itself, the time between two pulse pairs differs for each device.

Interference Scenarios

The occurring interference may be divided into different scenarios. For each scenario both DME and LDACS1 has to be considered as a victim system. In the following the different scenarios are described for those two systems.

To set the desired and the undesired signal power in the measurements into a relation, the Signal to Interference power Ratio (SIR) expressed in dB is employed.

$$SIR = \frac{P_{\text{desired}}}{P_{\text{undesired}}} \ [\text{dB}].$$

It is important to stress, that of both the victim and interfering transmitter its entire transmit power is taken into consideration. In reality an LDACS1 system experiencing interference by a DME transmitter in a different frequency band usually only receives a small fraction of the interference power due to the filtering performed at the receiver. However, since for the DME devices no information about its filter characteristics exists, the measure described is used in order to allow a better comparability between the two victim systems.

For the DME always the peak power of the signal is considered, since the signal can be seen as a constant waveform (CW) signal. Contrarily for the LDACS1 signal always the average power is used. This is due to the Peak to Average Power Ratio (PAPR) of LDACS1. Theoretically the PAPR of the OFDM signal is roughly 17 dB. However, the LDACS1 system limits the maximum PAPR to 12.4 dB.

Due to an intelligent allocation of the frequency bands of DME and LDACS1, the number of scenarios may already be reduced to a small number. The frequencies used by the system are shown in Figure 8, while Figure 9 shows all theoretically possible scenarios.

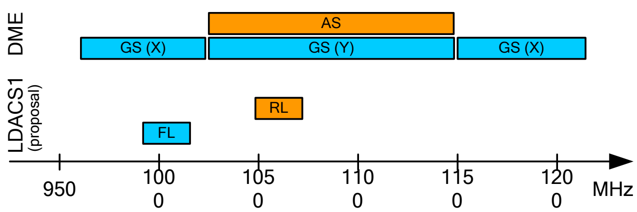

Figure 8. Frequency Allocation of DME and LDACS1

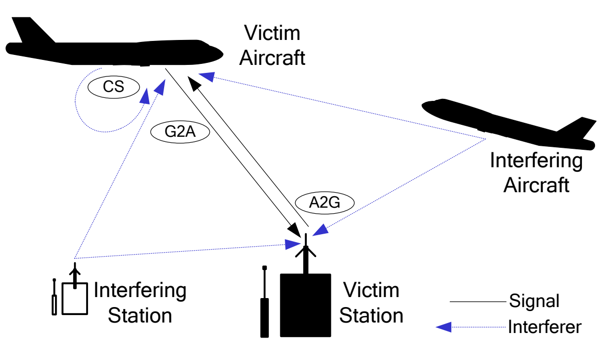

Figure 9. Possible Scenarios

Combining information from the two figures the following 3 relevant scenarios may be defined:

Ground to Air (G2A)

The signal from a GS is disturbed by a different interfering GS. In the case of an LDACS1 GS being the interferer, the reception of the DME responders' replies will thus be continuously disturbed by the time continuous FL signal. On the other hand the LDACS1 FL reception will be degraded by a high number of DME pulses, due to the DME GS usually serving a high number of different aircraft. As a worst case assumption the maximum allowed number of 2700 PPPS seems feasible.

Assuming a deployment of the LDACS1 stations at DME locations the signal to interference ratio at victim DME is generally limited. The distance from the DME and LDACS1 GSs to the AS is similar. Thus, due to its higher transmit power, the received DME power is usually roughly 30 dB higher than the interfering LDACS1 power. Therefore the SIR is at least 30 dB.

Compared to a situation of an LDACS1 AS being the victim system, the difference in power may possibly be higher. As example we can construct the following worst case: Assume an aircraft at height higher than the minimum height of 600 m allowed when flying directly over a DME station. The LDACS1 GS is seen just at the radio horizon and therefore the theoretically smallest power is received. Using that assumption and considering the correct transmit powers for the two GSs, the theoretically largest difference between the received LDACS1 and DME power level can be calculated. For the minimum height of 600 m this is about 72 dB. Note however that this is the theoretically worst case possible. It is unrealistic due to two reasons: Because of the antennas usually employed and its non-isotropic shape, the transmit signal from directly below is highly attenuated. Secondly, a scenario like this can easily be avoided by an effective planning of the GS. In general it is hard to come up with a realistic number due to its dependence in different parameters, especially the planning of the LDACS1 GSs' positions. A conservative estimate might be to assume an SIR of at least something around -50 dB [8].

Co-site (CS)

In the CS case the interferer is located on the same aircraft as the receiver. Therefore, the interfering power may be significantly higher compared to the desired signal. As a worst case scenario an SIR of -110 dB seems to be a reasonable guess. An LDACS1 FL signal is disturbed by a DME interrogation request and a DME reply is degraded by an LDACS1 RL transmission. However, due to the frequency separation between the DME AS and LDACS1 FL signals only the noise acts as an interferer not the transmitted signal itself. This will lead to a noise floor at the victim receiver rising significantly above the signal level while the interferer is active. Thus, the desired signal is most likely to be completely destroyed at that time. This event however will happen with a very low duty cycle, i.e. maximum of 150 PPPS from a DME interferer and 10 % from a LDACS1 RL transmitter under heavy load.

Air to ground (A2G)

In that scenario at least one aircraft is transmitting an interfering signal. A DME GS is disturbed by LDACS1 RL signal while an LDACS1 base station may be disturbed by the DME interrogators requests from an aircraft.

In the A2G scenario one interferer only transmits sporadically, however due to the high number of interferers possible, the overall duty cycle may increase. An advantage of the high number of aircraft is that, assuming that all aircraft are not located at the same position, most of the interferers are received with a moderate power level. However, a worst case scenario similar to the G2A case may be constructed: An AS trying to connect on a certain GS just on the radio horizon. Over the GS several interfering AS exist causing a degradation of the victim GS receive signal. Considering the transmit power of the AS the highest possible SIR in case of a DME victim receiver is -31 dB and for an LDACS1 victim roughly -63 dB. Note that this SIR value can only appear for one interferer directly over the GS. Again in this worst case antenna patterns are not considered, the actual SIR is thus expected to be at least 10 dB higher than the worst case.

Additional scenarios exist, but are not considered in this paper. The case were two GS are interfering with each other is not considered since it can most likely be avoided by an effective placement of the base stations and its antennas. Another problem might be the air-to-air case where the LDACS1 RL interferes with the DME GS station replies while in Y-mode. This, however, is very similar to the G2A scenario, with the difference that the victim receiver is not disturbed by a time continuous signal but rather a signal with a very low duty cycle. Thus, it is less severe and is therefore not considered.

Measurement Set-Up

For the two interfering systems different effects have to be evaluated in the measurements: Firstly, the influence of an LDACS1 TRANSMITTER on the interrogation process between the DME AS and GS. Secondly, the degradation of the LDACS1 system caused by a DME device has to be examined. Therefore in general two different set-ups are necessary. In the measurements the following equipment is used:

- DLR LDACS1 Prototype (consisting of Parsec LDACS1 prototype RX/TX FPGA system and Bögl & Partners Systemtechnik 10.7 MHz to L-Band RF frontend)
- RockwellCollins DME900 (DME AS used in air transportation)
- Bendix/King KDM-706A (DME AS used in general aviation)
- DME Ground Station simulator JCAir SDX 2000 (DME GS)
- Rohde & Schwarz RSG step attenuator
- Circulators, couplers, cables

The two measurement set-ups are shown in Figure 10. Couplers are used to superimpose the victim system with the interfering signal. Hence, the propagation channel is simplified to an adjustable attenuation.

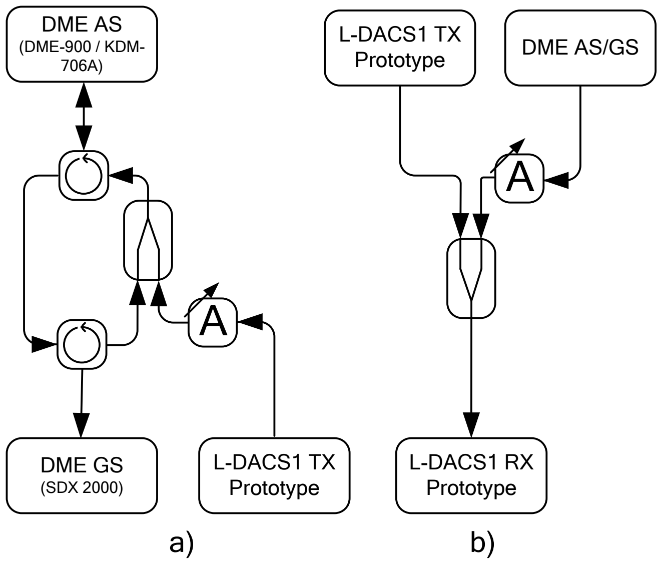

Figure 10. Schematic Measurement Set-up For a) LDACS1 on DME and b) DME on LDACS1 Interference Measurements

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 Figure 10a. The circulators are used to decouple the two paths between the base and airborne DME. Nevertheless, as described above, both paths are also separated in the frequency domain. 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 remains constant. All power levels are measured at the input of the victim DME system.

In the second set-up shown in Figure 10b the DLR LDACS1 receiver prototype is also required. As described above this prototype mainly functions as a down converter to the base band and data grabber. The I-Q samples are then processed using a software decoder. In the measurement, the LDACS1 transmitter and receiver are directly connected; the interfering DME airborne equipment is first attenuated by a step attenuator and then coupled in.

LDACS1 Demonstrator

The demonstrator set-up comprises the physical layer of the LDACS1 transmitter and the LDACS1 receiver. Since the transmission signal is defined in [5] and subject to only minor changes, an FPGA implementation of the complete LDACS1 physical layer including adaptive coding and modulation as well as the complete framing structure for forward and reverse link has been chosen for the LDACS1 transmitter. The FPGA implementation shows very strong advantages over a software implementation, where the necessity of pre-calculating the transmission signals reduces the flexibility during measurements. In addition, the FPGA based transmitter allows switching between the LDACS1 frame types for both the FL and RL and real time adjustment of transmission parameters, like coding and modulation.

As for any system, 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 has been chosen to be 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 cope with the interference introduced by systems such as DME, receiver has sophisticated algorithms allowing correct decoding of the data. Since that topic is out of the scope of this paper, for more details the reader is referred to [9].

Interference onto DME

In this part the results obtained in the measurements for the case of an LDACS1 interfering with a DME victim device are presented. For the different scenarios, the performance degradation is characterized in terms of the Time to Acquire (TTA) parameter. The TTA denotes the time a DME AS needs to obtain a lock on the distance to the GS. With DME devices currently used in aviation, like the ones considered during the measurements, the TTA is usually in the order of five seconds in the case of no interference present. In these measurements, if the DME board unit is not able to acquire a lock within TTA_{max} = 60 s, the try is deemed to be unsuccessful. The DME experiences a level of interference too strong for proper operation. In this case the level of interference is not tolerable.

Within the measurements the frequency of the victim DME AS receiver, the reply frequency of the interrogator, is always fixed to 1004 MHz. A crucial parameter for the measurements is the frequency offset Δf between the DME reply frequency and the LDACS1 TRANSMIT frequency. For the later employment, it is planned, that there will be an offset of at least 500 kHz. Therefore, in the measurements the main focus is put on that placement of LDACS1 in the spectrum. Nevertheless, the behavior for smaller offsets is also of interest showing the level of maximum LDACS1 interference, the DME receiver can cope with.

For all measurements the received DME signal power at the DME AS input is fixed to -82 dBm, a value at which a normal operation in the interference free case should be guaranteed. The interfering LDACS1 power is then adjusted in order to obtain the desired SIR.

Another relevant factor for the measurements is the modulation alphabet employed. In general, a 64QAM alphabet has turned out to cause a higher degradation of the DME's performance compared to lower order modulation alphabets. A possible reason might be the higher PAPR compared to QPSK and 16QAM. Therefore, for all measurements only the 64QAM alphabet is considered in order to cause the maximum degradation possible.

All tests have to be performed for several DME airborne devices as well as the two transmission modes in LDACS1, the RL and FL. These tests mainly focus on the DME900 device and partly on the KDM706A.

For each test at least 10 separate tries to obtain a distance lock are performed. Although this low number does not give reliable quantitative results, it allows a good approximation of the performance to be expected in longer tests. More precise results will be obtained in measurements planned for the future.

Forward Link (G2A)

For the evaluation of the G2A scenario the measurements have to be performed using the LDACS1 FL. As stated above the FL is a time continuous transmission, i.e. duty cycle is always equal to one. Thus, the degradation to be expected is assumed to be serious, since the DME is continuously interfered with. The two parameters to be varied are the frequency offset Δf and the SIR.

The results of the interference caused by an LDACS1 FL ground station on an airborne DME is shown in Figure 11. The SIR is plotted versus the corresponding TTA. The error bars denote the standard derivation of the measurement. The vertical dotted line denotes the first measurement, where at least one distance lock could not be obtained within the required 60 s.

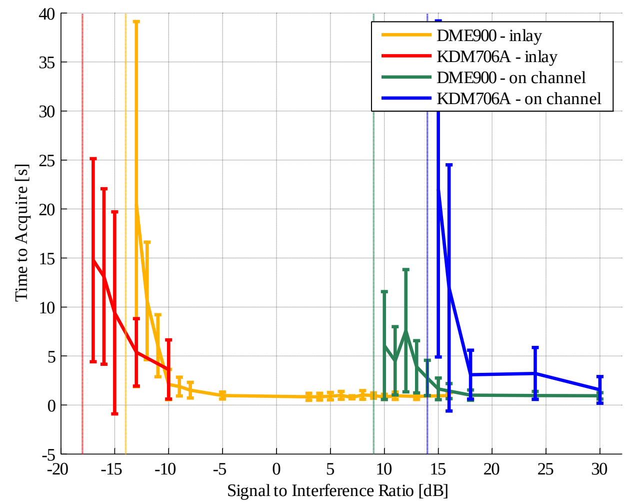

Figure 11. Interference on a DME Caused by the LDACS1 FL

For an LDACS1 transmitter placed with an offset of Δf = 500 kHz to a DME, i.e. the inlay configuration, the LDACS1 system has only a minor impact on the DME's performance in the relevant SIR range above 20 to 30 dB to be expected in a realistic G2A scenario. However, increasing the LDACS1 power significantly, leads to a degradation of the performance. The SIR has to be lower than -10 dB in order to cause a noticeable effect onto the measured TTA value. The smaller medium class KDM706A seems to be less sensitive to the LDACS1 interference. Compared to the high class DME900 unit, it tolerated up to 5 dB more interference. This behavior is somehow peculiar, however can not be explained since no inside knowledge of the device is available.

To allow an estimate of the maximum degradation caused by an LDACS1 FL ground station in Figure 11 also the results for the on channel deployment, Δf = 0 kHz, are shown. As expected this has a larger impact than the inlay case on the DME device to establish correct interrogation. Overall the SIR has to be roughly 15 dB to allow correct operation of the device. Comparing the two different devices shows a difference of 5 dB in terms of tolerating the interference. In this case DME-900 exhibits a higher performance.

Looking at the results of the measurements shows the high robustness of the DME system against interferers. As stated above in a realistic G2A scenario with co-location DME and LDACS1, the SIR to be expected is at least in the range of 30 dB. Using that assumption, even in the case of a ground station using the same band as the DME, its operation would still be easily possible with a safety margin of roughly 15 dB. Obviously, the impact in the case of an inlay deployment is even smaller, most likely undetectable. Therefore, in reality no remarkable degradation in terms of TTA performance is to be expected.

Reverse Link (CS, A2G)

As described above the RL employs transmissions from an aircraft to the ground, the two relevant scenarios are the CS and A2G case. One measurement for the on channel case is carried out. More results will be available in September 2011. In the measurement the following parameters are used: $\Delta f = 0$ kHz (on channel) and SIR = 50.2 dB. The duty cycle of the LDACS1 RL is then varied from 0 to 25 %.

A major problem in the RL measurement is connected to the hardware available in the first tests. Since no strong RF amplifier existed at that time, a limited range of SIR values can be expressed. The minimum SIR value possible with the set-up is -50 dB. The results for the measurement are shown in Figure 12. Since the LDACS1 power is fixed to -50 dB the x-axis shows the duty cycle. The TTA is again shown in the y-axis. Measurements were performed for a single device, the DME-900. The previous results indicate that no fundamentally different results for the two devices are to be expected.

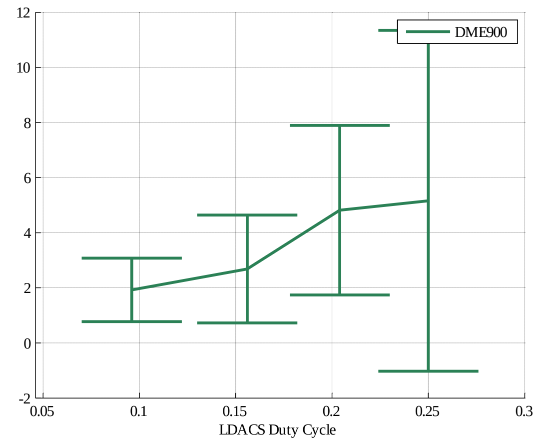

Figure 12. Interference on a DME Caused by the LDACS1 RL, SIR -50 dB

For the CS case some findings may be concluded, although the measurement does not completely match the actual CS scenario. As described above, the differences in power may turn up to be severe; the SIR can be as low as -110 dB. Nevertheless, the RL transmit signal and the DME's AS receive signal are separated in the frequency domain. Therefore, the major contribution in terms of interference is assumed to be caused by the spectral mask of the LDACS1 RL transmitter. The receiving DME AS device experiences a rise in terms of noise floor while an RL transmission is active.

As stated above the low SIR cannot be expressed without using a powerful amplifier. Therefore, for the measurements the LDACS1 RL is working in the on channel mode. Thus, an RL transmission effectively leads to a complete jamming of the entire DME frequency band similar to broadband noise. Because of the large differences in power a DME device is most likely not to work during that time. Hence, this case is very similar to the realistic scenario, the only difference is that the DME device is not mainly interfered by LDACS1 spectral mask but its actual signal.

The results in Figure 12 show that for the maximum duty cycle of 10 % currently allowed, the DME performance only experiences a very minor impact. Even increasing the DC to the very extreme value of 25 % only influences the operation of the DME marginally. These results have to be verified by a measurement with the correct frequency offset and

SIR, however a principal change of the findings for the CS scenario is assumed to be very unlikely.

Also for the G2A case, results may be concluded from Figure 12. This is done under the assumption that the DME GS' signal processing is not significantly differing from that of the AS. This is due to the measurements being carried out for an AS being interfered with. As stated above the minimum SIR for G2A to be expected at a victim receiver is about -30 dB from a single aircraft. Again a maximum duty cycle of 10 % for one aircraft is considered. However averaging over a longer period, the duty cycle of a single aircraft usually should not exceed 1 %.

Looking at the results shows that the tested device is more than fit to cope with the interference caused by the RL transmission. Instead of a realistic SIR of -30 dB the situation in the measurement is significantly degraded by another 20 dB. Additionally, LDACS1 transmits on the same channel like the DME AS. Even under these severe conditions for a duty cycle of 10 % the system works almost perfectly. Increasing the DC to the very extreme case of 25 % only leads to a very moderate increase of the TTA. A normal operation is still possible.

Overall it can be concluded that in any realistic scenario to proper functioning of the DME in the A2G case is not endangered by the existence of an LDACS1 RL transmission.

Interference on LDACS1

As for the DME above, also the LDACS1 system has to be considered as a victim receiver. In contrast to the previous situation, for LDACS1 the performance degradation is expressed in terms of BER and frame error rates (FER). For the BER a difference between the error rate before and after the decoder is made. As modulation alphabet always QPSK as well as the lowest possible coding rate of 0.45 is employed. This is reasonable since in situations with strong interference the system will always fall back to that alphabet and coding. The number of simulated bits was picked such as it can give reliable results to a coded BER of up to 10^{-5}.

Relevant results of the measurements are summarized in Table 1. For all measurements two different LDACS1 power levels at the input of the receiver are examined. A receive power of -98 dBm is 5 dB above the sensitivity level of the receiver and, therefore, simulates the normal operation of LDACS1. An input power of -95 dB is used as additional information on the general behavior of the receiver.

Table 1. Results for Interference on LDACS1

Scenario	P_{DME} [dBm]	P_{LDACS1} [dBm]	BER_{unc}	BER_{cod}	FER
G2A	-25	-98	4.4 %	0	0
		-95	3.5 %	0	0
CS	12	-98	2.9 %	0	0
		-95	1.6 %	0	0
A2G	-35	-98	1.21 %	$6.8 \cdot 10^{-6}$	$1.37 \cdot 10^{-4}$
		-95	1.17 %	0	0

Forward Link (G2A)

As described above the theoretical lower limit in terms of SIR can be approximated with -72 dB. The DME GS is assumed to be transmitting pulses at its maximum rate of 2700 PPPS.

Table 1 shows that in G2A scenario assuming worst case parameters, the LDACS1 FL can easily cope with the interference. The countermeasures within the receiver seem to work very effectively and the negative effects of the DME can be compensated.

Forward Link (CS)

For the CS scenario the interference of a DME device on the same aircraft is observed. As described in Figure 8 the LDACS1 FL and DME AS are separated in the frequency domain. The minimum frequency separation is obtained when a DME AS transmits in its lowest possible frequency, 1041 MHz, and an LDACS1 GS at its highest, 1008.5 MHz. This worst possible situation is used for this scenario. The KDM-706A DME AS is operated in search mode for the entire measurement. It is therefore transmitting pulse pairs at its highest rate of 100 PPPS.

The results show that the LDACS1 system is able to receive the FL signal by the GS correctly. Although the useful signal is most likely completely destroyed while a pulse pair is transmitted by the DME AS, both the coding and interference countermeasures allow a correct reception of the data.

Reverse Link (A2G)

The reception of the LDACS1 RL signal might be disturbed at the GS by DME AS. As stated above usually several DME interferers exist in the scenario. Therefore not a single device is used, but the DME GS device transmitting pulse pairs at a rate of 1000 PPPS. For the LDACS1 transmission the frequency of 1050.5 MHz and for the DME 1050 MHz are used.

Again the LDACS1 link seems to cope fine with that interference scenario. However this time coded BERs and FERs occur. This is mainly due to the fact that the RL coding blocks are of smaller size. Therefore, it is harder for the coding to correct the errors. Nevertheless, the performance is still more than sufficient. The automatic repeat request scheme (ARQ) employed in LDACS1 roughly needs a frame error rate of 10^{-2} for a proper operation.

Conclusion and Outlook

In this paper, the L-band compatibility of LDACS1 with the legacy system DME has been examined. Therefore, two victim systems with three different interference scenarios were considered. For all scenarios a worst case scenario was applied.

In the case of a DME victim system interfered with by LDACS1, for the ground to air scenario no degradation in terms of performance could be observed. Additionally the results from the measurement carried out strongly suggest that for the air to ground and co-site scenarios no degradation of the system's performance is to be expected.

Concerning the degradations caused on the LDACS1 system the results are very promising as well: In all scenarios the mitigation techniques in the receiver prove to be sufficient in order to guarantee a good performance of the data link.

For a concluding evaluation of the L-band conformance of LDACS1 a final series of measurements will be carried out in September 2011. These measurements are expected to validate the findings proposed herein.

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