Introduction

Currently, air-traffic management (ATM) is undergoing an extensive modernization process within SESAR [1] and NextGen [2] in Europe and the US, respectively. This includes also the development of the future communication infrastructure (FCI) [3] which is jointly carried out by Eurocontrol and the Federal Aviation Administration (FAA). Within the FCI, the L-band has been allocated for air-to-ground communications. Currently, two candidate systems for superseding the analogue voice communication system in the VHF band are taken into consideration. The first candidate L-band digital aeronautical communications system type 1 (LDACS1) is a broadband system employing orthogonal frequency-division multiplexing (OFDM) and frequency-division duplex (FDD). LDACS1 has been designed as a combination of P34 (TIA 902 standard) and the broadband aeronautical multi-carrier communications (B-AMC) system [4]. The second candidate LDACS2 is a narrowband single-carrier system utilizing time-division duplex as duplex scheme. This system is a derivative of the L-band digital link (LDL) and the all-purpose multi-channel aviation communication system (AMACS).

Introducing a new system in the L-band is a challenging task, since this frequency band is already utilized by different legacy systems. This includes aeronautical navigation aids such as the distance measuring equipment (DME) or the military tactical air navigation (TACAN) system as well as communication systems like the joint tactical information distribution system (JTIDS). In addition, fixed channels are allocated for the universal access transceiver (UAT) at 978 MHz and for secondary surveillance radar (SSR)/airborne collision avoidance system (ACAS) at 1030 and 1090 MHz.

In order to provide a high transmission capacity while preserving the channel allocations of the legacy systems the LDACS1 system would be preferably deployed using an inlay approach. In this case the system tries to employ the spectral gaps between channels, which are used by the legacy systems. This approach leads to interference from LDACS1 onto the legacy systems, as well as interference from the legacy systems onto LDACS1. The first issue is investigated in [5]. In this paper, we concentrate on the influence from the different legacy systems onto LDACS1 [1]. Such an investigation is required to achieve the following goals which are important for the LDACS system design:

- Identification and characterization of the relevant interference sources in the L-band. This is necessary to subsequently develop appropriate mitigation techniques for LDACS1 receivers.
- Modeling of the different interference sources to enable LDACS1 performance simulations under interference impact. Given a desired bit error rate (BER) below 1×10^{-6} for an LDACS1 transmission, such simulations lead to requirements on the signal-to-noise ratio (SNR) of the transmission, which are essential for the link budget design of LDACS1.

LDACS1 System Parameters

In this section, a short overview of the LDACS1 system is given, focusing on the system characteristics being relevant for the inlay approach and the robustness against interference. For more detailed information see the LDACS1 system specification [7].

Main System Capabilities

LDACS1 is intended to operate in the lower part of the L-band (960-1164 MHz). It is designed as a FDD system, which enables a ground station (GS) to transmit continuously at a certain frequency, while the connected airborne stations (AS) transmit in parallel at a different frequency. LDACS1 follows a cellular point-to-multipoint concept, where ASs within a certain volume of space, referred to as cell, are connected to a controlling GS. In regular operations, the maximum number of ASs per cell is 208. This number might be extended to up to 512 if required and traffic load allows. The cell size ranges from a few nautical miles (NM) for airport cells to typically 120 NM for en-route cells. In principles, the cell size is only restricted by foreseen guard times which limit the cell size to a maximum of 200 NM. Note, the cell size might be reduced to arbitrary values below 200 NM as long as the transmit power is adjusted accordingly. This ensures that no inter-cell interference issues occur with smaller cell sizes.

[1] The investigation in this paper is based on [6].

For the LDACS1 deployment in the L-band different scenarios are possible. The most challenging approach is the inlay scenario where the LDACS1 channels with a bandwidth of approximately 500 kHz are placed in between the existing DME channel grid of 1 MHz with an offset of 500 kHz to the DME center frequencies, as explained in the next section. This approach allows an LDACS1 deployment without changing existing DME assignments. For the inlay scenario the frequency range from 985.5 to 1008.5 MHz is foreseen for the forward link (FL) from GS to AS, whereas the return link (RL) from AS to GS is placed in the frequency range from 1048.5 to 1071.5 MHz. This choice minimizes the mutual interference between LDACS1 and other L-band systems, mainly SSR and UAT.

The LDACS1 signal is a multi-carrier signal, based on OFDM technology. The FL is a continuous OFDM transmission while in the RL a certain number of subcarriers are assigned for a certain duration to different users on demand, which is referred to as orthogonal frequency-division multiple access (OFDMA). This enables aircraft to adopt their transmission duty cycle and the allocation of different subcarriers according to the current interference conditions. Another feature which is integrated into LDACS1 is adaptive coding and modulation with different channel coding rates and modulation schemes supported. This enables the system to adapt the throughput and the robustness of the transmission to the current interference situation.

Selected Parameters

The channel bandwidth of approximately 500 kHz is used by an OFDM system with 50 subcarriers, resulting in a subcarrier spacing of about 10 kHz. This value was chosen as a trade-off between a high spectral efficiency and an acceptably low inter-carrier interference caused by Doppler shifts and spreads. In [8], it is shown that depending on the flight phase Doppler shifts of up to 1.25 kHz and Doppler spreads of up to 624 Hz may occur.

For OFDM modulation, a 64-point fast Fourier transform (FFT) is used. The total FFT bandwidth comprising all subcarriers is 625.0 kHz. Besides the 50 subcarriers used for transmission, the 64 subcarriers comprise one empty DC subcarrier as well as seven empty subcarriers at the left edge of the spectrum and six at the right edge serving as guard bands. Note that pilot subcarriers are inserted which are used for the estimation of the transmission channel at the receiver. According to the subcarrier spacing, an OFDM symbol has a duration of 102.4 µs. Each OFDM symbol is extended by a cyclic prefix of 17.6 µs, comprising a guard interval of 4.8 µs as well as 12.8 µs for transmit windowing. The guard interval provides resistance to inter-symbol interference caused by multipath effects. Transmit windowing leads to a reduction of the out-of-band radiation. This results in a total OFDM symbol duration of 120 µs.

Framing Structure

OFDM symbols are organized into LDACS1 frames. Depending on their functionality, different frame types are distinguished.

The frames are arranged into multi-frames (MF) and super-frames (SF). The structure of a SF is depicted in Fig. 1.

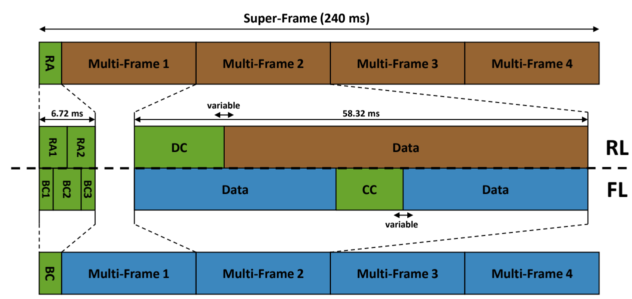

Fig. 1. Structure of an LDACS1 super-frame for forward and return link.

One SF consists of one broadcast (BC) frame in the FL and one random access (RA) frame in the RL, respectively, and of four MFs in both FL and RL. Each MF itself contains nine data/common control (CC) frames in the FL and one dedicated control (DC) segment and one data segment in the RL. The particular structure and functionality of the different frame types is described in [7]. Exemplary, a FL data/CC frame is depicted in Fig. 2. The synchronization symbols at the beginning of each frame are used to update the time and frequency synchronization at the receiver.

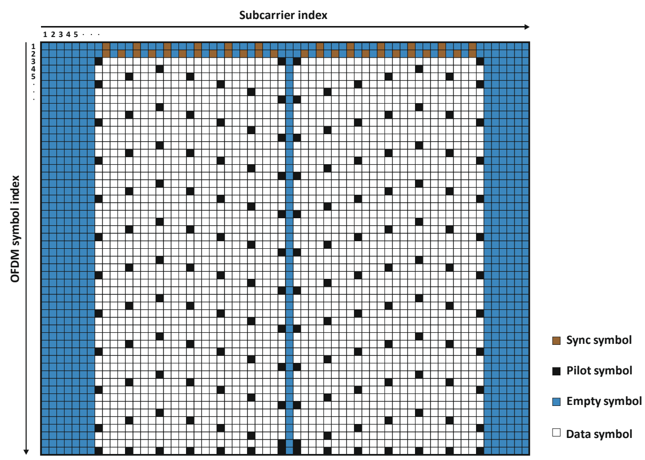

Fig. 2. Structure of an LDACS1 data/CC frame in the time-frequency plane indicating the different types of symbols.

Characterization of Interference

To identify systems which will interfere with LDACS1, we first have a look on the current L-band usage shown in Fig. 3. There are two types of interfering systems. Firstly, systems which partially overlap with the LDACS1 spectrum such as DME and JTIDS. Secondly, co-site systems which are equipped onboard an aircraft, such as airborne DME, UAT, and SSR. As illustrated in Fig. 3, these systems operate at different frequencies than LDACS1, but due to inevitable antenna coupling at the aircraft they cause significant broadband noise. As co-site interference occurs only at airborne receivers we focus on this case, i.e., the LDACS1 FL transmission.

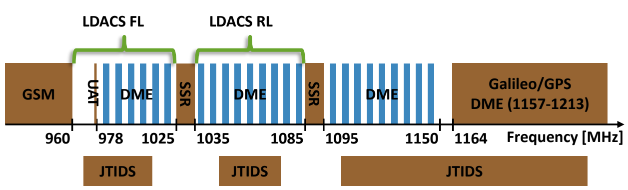

Fig. 3. Overview of frequency assignments for systems currently operating in the L-band and intended assignment of LDACS1 frequencies.

The influence from the legacy L-band systems onto LDACS1 can be assessed by means of the following parameters:

- Signal-to-interference ratio (SIR) at the LDACS1 receiver, i.e., the ratio of the received LDACS1 signal power and the received signal power of the interfering legacy system.
- Spectral overlap, i.e., the fraction of the LDACS1 bandwidth which is affected by the interference.
- Interference duty cycle, i.e., the fraction of time the LDACS1 receiver is exposed to interference.

In the following the different legacy L-band systems are presented and their interference influence is given in terms of the three attributes specified above.

Distance Measuring Equipment

When LDACS1 is deployed as an inlay system between adjacent DME channels, DME signals represent the most severe interference towards LDACS1. DME signals consist of pairs of Gaussian shaped pulses as shown in Fig. 4. They are characterized by the spacing Δt of the pulses. The value of Δt depends on the certain mode of the DME station, e.g. $\Delta t = 12\ \mu s$ for X mode. The different modes are explained in [9]. The parameter α characterizes the width of a Gaussian shaped pulse. For DME, the width is 3.5 µs at 50% of the maximum amplitude.

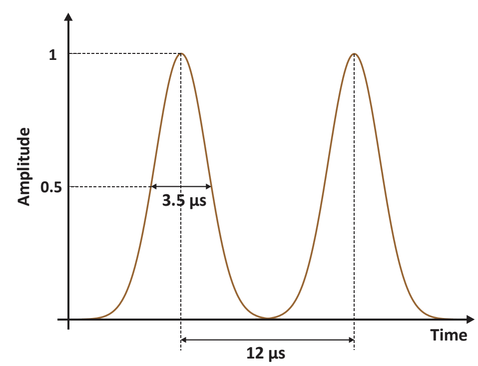

Fig. 4. Normalized amplitude of DME pulse pair in time domain (X mode).

Each DME transponder on ground transmits at a fixed center frequency on a 1 MHz channel grid in the range from 960 - 1215 MHz. The system is used for navigation purposes by ranging between an AS and a GS. A DME is usually coupled with a VOR device [9], which then allows, together with using knowledge about the altitude, the determination of the current position of the aircraft.

A Gaussian shaped pulse also leads to a Gaussian shaped spectrum. Since pulses are occurring pair-wise, the spectrum is modulated with a cosine. Fig. 5 shows exemplarily a 2 MHz detail of the L-band, comprising signals from two adjacent DME channels. In addition, an LDACS1 channel in between the two DME channels is shown.

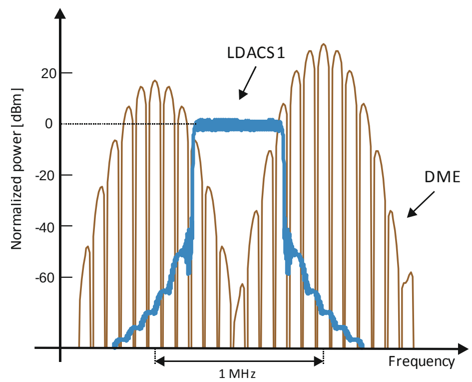

Fig. 5. Power spectral density of two adjacent DME channels with inlay LDACS1 channel.

The DME transmission rate is given by the number of pulse pairs per second (ppps). An airborne DME interrogator transmits up to 150 ppps in search mode. When a connection to a ground DME transponder could be established, the rate decreases to 30 ppps in track mode. The pulse rate of a DME transponder depends on the number of aircraft it has to serve. In maximum, 2700 ppps is reached [10]. The typical transmit peak power of DME ground transponders can be given by 1 kW, corresponding to 60 dBm. Airborne interrogators transmit with 63 dBm [11].

TACAN is a military navigation system similar to the DME system. In contrast to DME, it is capable of calculating not only the distance between a GS and an AS, but also the direction of the transponder signal at the aircraft. Therefore, a TACAN transponder transmits 900 specially coded ppps, augmenting the maximum pulse rate to 3600 ppps. The GS transmit peak power is 3 kW, i.e. 64.8 dBm.

Signal-to-interference ratio
The transmit power of DME/TACAN is significantly above the maximum LDACS1 transmit power, which is 41 dBm. Hence, unless an aircraft is located in the vicinity of an LDACS1 GS, the SIR at an airborne LDACS1 receiver will be very low when receiving DME/TACAN signals from adjacent channels. In [6], it is derived that in certain situations, the DME/TACAN peak power is 50 dB above the LDACS1 power at the receiver.

Spectral overlap
As clarified in Fig. 5, the DME/TACAN signals affect only the edges of the LDACS1 spectrum, since an LDACS1 channel is always placed in between two adjacent DME/TACAN channels with 500 kHz offset.

Interference duty cycle
The interference duty cycles of DME/TACAN signals can be calculated based on the fixed pulse rates and pulse width; we obtain 4.6% for a DME and 6.1% for a TACAN station in the FL. Investigations showed that typically an AS is exposed to interference from one GS. In severe cases, up to three TACAN stations might be active in the adjacent channels [12] leading to a cumulated worst case duty cycle of 17.2%. Details about the calculations can be found in [6].

Co-site Interference

Co-site interference occurs due to inevitable antenna coupling between transmit antennas of legacy systems and the LDACS1 receive antenna, all of them equipped on-board an aircraft. Obviously, this is no matter at the GS, where a sufficiently high antenna isolation can be guaranteed. Although the on-board legacy systems, namely DME, SSR, and UAT, transmit at frequencies well separated from the LDACS FL center frequencies, the power of the occurring broadband noise is not negligible at the LDACS1 AS receiver.

Signal-to-interference ratio
In [6], the expected interference power of these three systems at the LDACS1 AS receiver is derived. Taking the spectral masks of the different systems and a realistic antenna isolation of 35 dB into account, the SIR is below -60 dB. Hence, the broadband noise power of all three systems is significantly above the LDACS1 sensitivity level.

Spectral overlap
As co-site interference occurs as broadband noise, the whole LDACS1 bandwidth is affected.

Interference duty cycle
The DME interrogator pulse rates are given above and lead to a duty cycle of 0.26% in search and 0.05% in track mode. UAT frames last 1 s. Within this frame, an aircraft can transmit either one short or long ADS-B message, lasting 276 µs and 420 µs, respectively. This leads to duty cycles of 0.28 % or

0.42%. Finally, the duty cycle of SSR shall be given. It is a sum of different radar techniques like mode A/C, TCAS, or the extended squitter, which are comprised within the SSR system. In [10], a typical and a worst case scenario for the occurrence of SSR pulses is defined. Accordingly, a typical duty cycle of 0.43% and a worst case duty cycle of 0.84% are derived.

When keeping the DME/TACAN duty cycles in mind, we can conclude that the co-site interference influence is negligible compared to DME/TACAN interference, although it affects the entire LDACS1 bandwidth.

Joint Tactical Information Distribution System

JTIDS is a digital military radio system, mainly used by the NATO. It is based on time-division multiple-access (TDMA) and provides a jam-resistant mode by employing frequency hopping in a pseudo-random way. Therefore it uses 51 frequencies in the frequency band 960 - 1215 MHz, excluding areas around the SSR frequencies 1030 and 1090 MHz. The 51 frequencies have 3 MHz spacing. The smallest unit in the TDMA framing is a pulse with duration of 13 μs, comprising a 6.4 μs active pulse time with a trapezoid pulse shape and 6.6 μs guard time. The frequency hopping is applied pulse by pulse. This pulse by pulse frequency hopping scheme is depicted in Fig. 6 for a short time period.

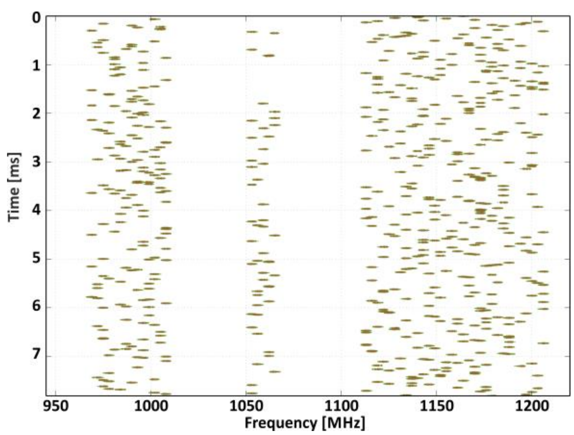

Fig. 6. Frequency hopping principle for JTIDS pulses in the L-band, possibly interfering with LDACS1 signals.

Signal-to-interference ratio

In principle, the maximum allowed transmit power of a JTIDS transmitter is 1 kW. However, most national frequency clearance agreements (FCA) limit this power to 200 W (53 dBm). This is 12 dB above the maximum LDACS1 transmit power, leading to SIR = 0 dB, if the distance between JTIDS transmitter and LDACS1 receiver is roughly four times the distance between LDACS1 transmitter and receiver. Hence, for most geometric constellations, the SIR is significantly below zero when JTIDS pulses coincide with the LDACS transmission. This is the case when the currently used JTIDS hopping frequency overlaps with the LDACS transmission bandwidth.

Spectral overlap

According to the spectral mask depicted in Fig. 7, the JTIDS spectrum is flat within a bandwidth of ± 3MHz. This is significantly larger than the LDACS1 bandwidth of 500 kHz leading typically to a flat interference spectrum.

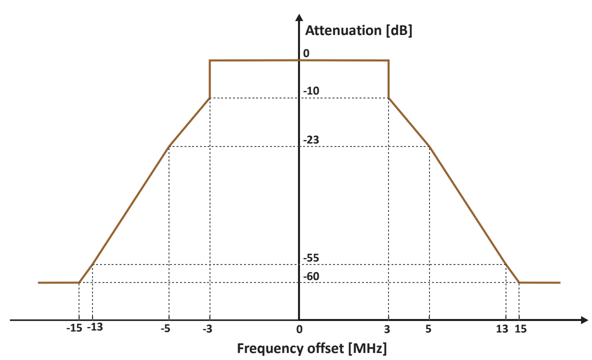

Fig. 7. Spectral mask of JTIDS transmit signals.

Interference duty cycle

The derivation of the JTIDS interference duty cycle at an LDACS1 receiver is not simple as many factors have an influence. First, the number of JTIDS networks which are active in a certain area. Next, the maximum number of time slots a single user may allocate. In addition the number of hopping frequencies which interfere with an LDACS1 channel. This number depends on the distance between JTIDS interferer and LDACS1 receiver and the attenuation for a certain frequency offset (see Fig. 7). In total this leads to a typical duty cycle of 1.1% and a worst case duty cycle of 6.4%. The detailed derivations can be found in [6].

Influence of Interference

In the following, the influence of interference from legacy L-band systems onto LDACS1 is evaluated. Other effects which might impact the LDACS1 performance are not taken into account for simplicity. In particular, a standard additive white Gaussian noise (AWGN) channel but no additional time-variant multi-path channel is assumed. Actually, this simple model is very close to reality, especially for the en-route case due to the dominant line-of-sight path present in this environment as discussed in [9].

To assess the influence of the different L-band interference sources on LDACS1, BER simulations are carried out using an interference model as described in the following. As derived in the previous section, in most cases the interference power is significantly above the LDACS1 signal power at the receiver. Hence, we assume that the interference can be detected nearly perfect which was also verified in [6]. Based on this perfect detection of the interference, the LDACS1 signal is blanked, i.e., set to zero. The duration of the blanking intervals is chosen according to the characterization of the different interference sources from the previous section. The starting points of the blanking intervals for the different sources of interference are determined by a stochastic Poisson process. In Fig. 8, the BER of the LDACS1 FL is plotted versus the SNR for the different sources of interference.

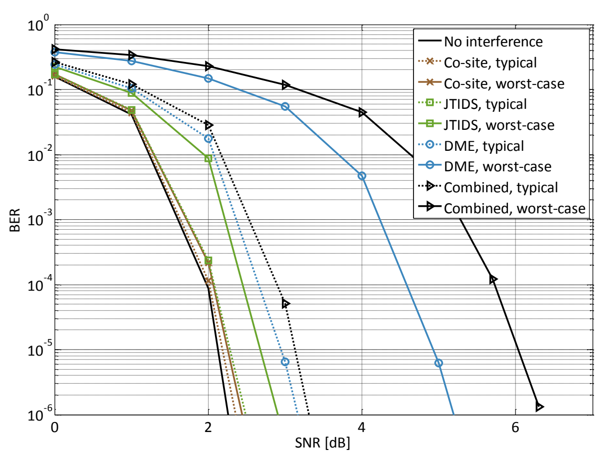

Fig. 8. BER vs. SNR for LDACS1 forward link transmission with AWGN and different interference conditions.

The co-site interference leads, even in the worst case, to no remarkable system performance degradation. The same holds for a typical JTIDS interference scenario. For these interference scenarios, the desired BER of $1\text{x}10^{-6}$ leads to an SNR ≈ 2.5 dB. The worst case JTIDS scenario leads to a recognizable performance degradation which is still little. As expected, interference from DME/TACAN stations leads to a significant performance loss. In a typical case, with one strong station in an adjacent channel, the system degradation is around 1 dB. In a worst case environment, the degradation is around 3 dB. For the combined interference, the loss is roughly the sum of the individual losses. This leads to a loss of approximately 4 dB in the worst case corresponding to a required SNR ≈ 6.5 dB. Although this loss is still moderate, it can be further reduced. To mitigate the interference, only pulse blanking but no additional methods are considered in this paper. When applying more sophisticated interference mitigation as described e.g. in [12], a considerable performance re-gain is achieved.

Conclusion

In this paper, we addressed the interference situation a future aeronautical communications system in the L-band is exposed to. We introduced the system parameters of the broadband candidate system LDACS1. Next, we presented and characterized the different legacy systems operating in the L-band in terms of their spectral characteristics, their interfering power, and the duty cycle and derived typical and worst case scenarios for their impact onto LDACS1. It turned out that DME represents the most severe source of interference for LDACS1, while the detrimental influence of co-site interference is negligible. The interference from JTIDS is recognizable but still little even for the worst case scenario. In addition, performance simulations for the combined interference show that even for the worst case scenario the desired BER is achieved for moderate SNR conditions.

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