HOW THE L-DACS2 RADIO-FREQUENCY SIGNALS MODULATION AFFECTS THE DME PERFORMANCE

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Abstract

In this paper, we consider the Radio-Frequency Compatibility (RFC) of a candidate system within future aeronautical communication infrastructure, being developed since 2004 to accommodate the evolution of the aeronautical environment. The system presented in this paper is one of the two preselected proposals for the L-band Digital Aeronautical Communication System (LDACS), in charge of the continental communications. It is named L-DACS2 and will use the 960 to 1164 MHz band, allocated to the Aeronautical Mobile Service reserved for communications relating to safety and regularity of flight. This band is characterized by a very dense spectral occupation by a large number of aeronautical systems. The RFC (branch of electrical science that studies the coexistence of radio systems in the same electromagnetic environment) is very important for L-DACS deployment and if it is not satisfied, the flight safety could be endangered. We propose to study in this paper the impact of the LDACS2 on the Distance Measuring Equipment (DME), which has been using the L-band for decades. According to recent studies performed in the frequency domain (continuous transmissions and no time domain variations), the achieved RFC level seems insufficient. The objective of this work is to analyze the RFC between LDACS2 and DME considering the time domain aspects of both systems. The idea is to quantify the impact of the radio-frequency signals generated by L-DACS2 interferer (transmitter) on the performance of a DME victim (receiver). The study is performed for the co-site case (equipments onboard of the same aircraft). To study the RFC between the two systems, we investigate various modulations for the future communication system. The results are obtained through computer simulations and laboratory measurements with an aeronautical testbed using a commercial DME unit. The DME performance degradation is evaluated for some values of the Signal to Interference Ratio.

Introduction

According to the aeronautical authorities, the aerial traffic forecast will be in a continual increase after 2011 [1]. Hence, in the coming decades, more than twice the number of airplanes will be present in the aeronautical network. To accommodate this evolution, communication with higher data-rates will be fundamental to provide better safety and fulfill the new requirements [2]. Employing such features in avionics will also enable new services. However, current systems for Air Traffic Management and Air Traffic Control, which use the aeronautical VHF band (118-137 MHz), are insufficient to fulfill these new requirements.

For this reason, the International Civil Aviation Organization launched a joint Euro-American project in 2004 to develop a Future Communication Infrastructure (FCI) adapted to this new aeronautical scenario. This project entitled the Future Communication Study started with a Cooperative Research Agreement (Action Plan 17) and is composed of researchers, industrial partners and aeronautical authorities from many countries around the world. The FCI will use complementary technologies across multiple frequency bands to provide both data and voice communications [3].

L-band Digital Aeronautical Communication System (L-DACS) is the proposed system for the continental communications and will use the 960-1164 MHz band, which is a part of the aeronautical L-band (960-1215 MHz) [4]. Despite its large potential spectrum, the L-band is a challenging environment due to its current spectral use by aeronautical, telecommunication and satellite systems. Hence, it is very important to study the Radio-Frequency Compatibility (RFC) of L-DACS with all the systems already in operation in the L-band and its adjacent bands. So far, two L-DACS candidates have been preselected and in-depth studies are being carried out before the final selection.
We focus herein on one of these two candidates, named L-DACS2 [5]. This system is widely inspired from the Global System for Mobile communications (GSM), which is the most popular standard for mobile telephony systems in the world. L-DACS2 is based on Time Division Duplex (TDD) and is expected to operate in the 960-975 MHz band. Our contribution is to address its RFC with one of the other L-band systems called Distance Measuring Equipment (DME). The DME is a very important worldwide radio navigation system operating in the 962-1213 MHz band, for which the communication is based on a succession of Gaussian pulse pairs that are exchanged between an onboard interrogator and a ground transponder. According to previous studies performed in co-channel mode (where the transmitter and the receiver use the same center frequency) and without taking into account the time domain aspects, the obtained compatibility level seems insufficient.

Thus, we analyze the RFC level including the time characteristics of both systems. We quantify the L-DACS2 effect on the DME performance in the co-site case, which is the most critical interference scenario due to the spatial proximity of both systems (equipment onboard the same airplane). We study the DME performance degradation with respect to the Signal over Interference Ratio (SIR) for different modulations of the L-DACS2 interfering signal. We investigate well-known digital modulation schemes that could be employed by the L-DACS2, in addition to its specified Gaussian Minimum Shift Keying (GMSK) modulation. We consider the Binary Phase Shift Keying (BPSK), Quadrature Amplitude Modulation (QAM) and Minimum Shift Keying (MSK). We performed the RFC studies using Matlab simulations and laboratory measurements. For this second method, we build a test-bed for the co-site scenario with a DME interrogator, a DME transponder and an L-DACS2 transmitter.

The paper is organized as follows. First, we present our approach to study the RFC. Then, we provide a better insight about the two systems and we detail the interference scenario. After that, we will implement this scenario through simulations and laboratory measurements. We focus in more details on the second approach. Finally, we will finally provide the main results for the different L-DACS2 modulations.

RFC classical and novel approach

Importance of the RFC

The RFC determines if radio systems can coexist in the same electromagnetic environment. Two systems A and B are compatible if each of them operates correctly in the presence of the other without generating harmful interference on the latter.

The RFC is very important for the L-DACS development project. It is necessary for the flight safety and is an essential criterion for the feasibility of the L-DACS technology. In fact, a large number of equipments are nowadays operating in the 960-1164 MHz band, but other systems using the adjacent bands should be also considered for RFC investigations (see figure 1). These systems (radionavigation, telecommunication and satellite systems) are in use in ground and aircrafts and they have different characteristics and functioning modes.

Figure 1. Spectral occupation and systems in use in the 960-1215 MHz (reference [6])

To study the RFC of L-DACS with these systems, different interference scenarios should be considered, as shown in figure 2.

Figure 2. Interference scenarios L-DACS vs. the L-band systems
Based on specific parameters of the transmitter (interferer) and the receiver (victim), the RFC study aims to compare in a given interference scenario the generated “unwanted” power density \( I_d \) at the victim’s antenna port and its interference density threshold \( I_{\text{max}} \). More details about these parameters can be found in [7] and [8].

**RFC classical approach**

So far, RFC investigations have been evaluated in the frequency domain. The idea of this classical RFC approach is to determine the minimal frequency separation between the victim and its potential interferers such as \( I_d < I_{\text{max}} \). This methodology has been used in the frequency sharing studies among systems in the L-band and its adjacent bands and based on five steps:

- Interference scenario (see figure 2): location of the interferer(s) and the victim,
- Interferer characterization
- Victim characterization
- Interference path: propagation model and interferers spatial/frequency distribution
- Link budget analysis

Previous studies in the frequency domain for L-DACS candidate systems show that the obtained RFC results seem insufficient when the transmitter and the receiver use the same or close frequency channels [7]. Under the classical approach, the interferers transmit continuously in time and the victim is likely to receive unwanted signals permanently. Indeed, the interference thresholds of L-DACS and L-band systems are low while their transmit powers are high given their operational ranges.

**RFC novel approach**

Hence, we propose to study the RFC taking into account time domain characteristics of the studied systems. According to the specifications of these systems, the transmitted signals are pulsed in the time domain. Under this novel approach, the interference is no longer continuous but occurs when the interferer transmits radio-frequency signals. Hence, to quantify the RFC level, it is important to define the time domain characteristics of the interfering signal, such as its modulation, its power and its duration. We define the channel occupation rate as the percentage of time during which the systems transmits radio-frequency signals. We also define the signal to interference ratio by the ratio between the interfering peak power and the useful peak power. We analyze the obtained RFC level in the time domain for a specific interference scenario where the interferer is an L-DACS candidate and the victim is an L-band legacy system. We study the effect of the L-DACS signal modulation on the RFC.

**Interference scenario**

We analyze the effect of the future L-DACS2 radio-frequency signals on the performance of a legacy L-band system, named the Distance Measuring Equipment (DME).

**Systems presentation**

The L-DACS2 [5] is one of the two candidates preselected to the aeronautical continental communications proposed by the European Organization for the Safety Air Navigation (EUROCONTROL). L-DACS2 is widely inspired from the Global System for Mobile communications (GSM), which has been deployed all over the world and it is originated from two main standards: the All-purpose Multi-channel Aviation Communication System (AMACS) and the L-band Data Link (LDL) standard. The L-DACS2 is based on a Time Division Duplex (TDD) technique, i.e. an alternation between messages from a Ground Station (GS) and a Mobile Station (MS) using the same carrier. These messages are exchanged within successive one second frames.

The DME [9] is an aeronautical radionavigation system has been in use since near a century and is implemented in all the aircrafts to have permanently their distance from ground stations. The DME communication is based on exchange of Gaussian pulse pairs between an onboard device (interrogator) and a ground beacon (transponder). The communication starts on the interrogator which transmits a pulse pair stream to the transponder. After a certain delay, the latter transmits back the received stream to the interrogator. By measuring the time between transmission and reception, subtracting the delay, multiplying by the speed of light and dividing by two, the interrogator gets its distance from the transponder.
Scenario description

We study the RFC between these two systems in the co-channel mode (that is, when they are using simultaneously the same center frequency). In fact, L-DACS2 and DME are foreseen to operate in the same frequency range. Following their specifications, the L-DACS2 is expected to use the 960-975 MHz spectrum and the DME is using the 962-1213 MHz band.

In addition, we choose to analyze the RFC in the case that the L-DACS2 interferer and the DME victim receiver are onboard of the same aircraft. This scenario is named the co-site scenario, and it is the most critical situation for the RFC because of the geographic proximity of the two equipments.

Scenario representation

To represent the RFC scenario, three equipments are essential: a useful transmitter, an interferer and a victim. Given that the study corresponds to the co-site scenario, both the interferer and the victim are onboard of the same airplane. Hence, the interferer is an L-DACS2 mobile station, the victim is a DME interrogator (INT) and the useful transmitter is a DME transponder (TRA).

The interference process is emulated based on three main steps. In the first step, the INT generates a Gaussian pulse-pairs stream to the TRA. In the second step, the TRA transmits back the received stream to the INT. In the third step, the L-DACS2 TX interference is added to the TRA transmission. The sum of both signals is transmitted to INT. We show the RFC scenario in figure 3. Two circulators are added for both INT and TRA to enable the switching between transmit and receiving functions.

DME performance degradation

Because of the possible collision with the interfering L-DACS2 signal, some pulse pairs sent by the transponder (step 2) may not be received by the interrogator (step 3). As a result, the DME system performance degrades. Let us define Rate as the ratio of the number of correctly received pairs (step 3) over the total number of sent pairs (step 1). If after a certain time delay (called maximum synchronization time), Rate is lower than a certain level (depending on the DME performance), the synchronization between the interrogator and the transponder fails.

Figure 3. L-DACS2 over DME: scenario representation

We study herein the synchronization failure for different modulations of the L-DACS2 interfering signal, with respect to L-DACS2 signal duration and for several values of the L-DACS2 power. For this, we investigate different well known modulations, such as the Binary Phase Shift Keying (BPSK), Quadrature Amplitude Modulation (QAM) and Minimum Shift Keying (MSK), in addition to the Gaussian Minimum Shift Keying (GMSK) modulation, which is the mentioned modulation in the L-DACS2 specifications.

Implementation

To emulate the scenario described in the previous section, we generate both L-DACS2 and DME time-domain signals. We study the resulting interference using these signals and its effect on the performance of the DME receiver, based on two different approaches: computer simulations and laboratory measurements.

Simulations

Assumptions

In this first approach, it is important to model the DME receiver in order to evaluate its performance degradation. However, such information is not available in the literature. Thus, we simulate the scenario based on two main assumptions. We first consider that a DME pulse pair is lost when it overlaps with the L-DACS2 interfering signal.

In addition, we assume that the DME transponder is perfect, which means that all the pairs received by the transponder are transmitted back to the interrogator.
Metric
Under the first assumption, the DME performance degradation is determined by the collision rate between L-DACS2 and DME messages. The collision rate is the percentage of DME Gaussian pairs that overlap with the L-DACS2 signal. In addition, thanks to the second assumption, we get the maximum collision rate for a given DME message.

Methodology
To get the collision rate, we generate both signals in the maximal synchronization time window. We create the signals randomly each second using a Monte Carlo approach. As the collision rate depends only on the L-DACS2 channel occupation rate, we represent the L-DACS2 signals by rectangular windows as wide as the signal durations. We apply the same process to generate each DME pulse pair.

Experiments

Equipments
In this approach, we implement an aeronautical test-bed to emulate the interference scenario. To represent the interference scenario of figure 3, we use three devices. INT is a commercial DME Bendix KN62A device, TRA is a commercial DME Aeroflex IFR6000 Ramp test and TX is a Vectorial Generator Agilent E4438C ESG.

Metric
Using this approach, the measured DME performance degradation is determined by the observed synchronization state between INT and TRA. This state is equal to 1 when the DME equipments are synchronized and 0 unless. When the equipments are synchronized, the interrogator screen indicates the carrier and the distance from the transponder (on the left and on the right respectively) as shown in figure 4. Otherwise, the distance is not displayed after synchronization time expires.

Methodology
To evaluate the L-DACS2 signal effect on the DME performance, we proceed as follows. First, we generate the L-DACS2 signal using the different modulations (BPSK, PSK, QAM, MSK and GMSK). For each modulation, we vary the interference power (L-DACS2 peak power) and we fix the useful power (TRA peak power). For each obtained Signal to Interference Ratio (SIR), we progressively increase the L-DACS2 channel occupation rate until the DME synchronization state drops to zero.

RFC laboratory measurements
According to the simulation approach, the L-DACS2 signals are assumed to be rectangular. Thus, in the simulation approach, the results will not depend on the modulation of the L-DACS2 signal. Therefore, in this section, we focus on the experimental implementation of the interference scenario to study the effect of this parameter on the DME performance.

Generation of the interfering signal
To generate the interfering signal, we create the baseband signal in a computer using Matlab tool and then we inject it to the vectorial generator through specific software, the commercial Agilent N7622A Signal Studio Toolkit. This tool imports the analog baseband waveform (In-phase and Quadrature data files), controls the signal generator parameters such as the frequency carrier and the signal peak power, and adjusts the sample clock of the generator to avoid the distortions and discontinuities on the RF signal. Once the signal is injected, we pilot its channel occupation rate using some functions of the vectorial generator.

In our specific test bed, the interferer is an L-DACS2 transmitter. We describe in the following subsections the generation process of the baseband signal for different modulations based on the specifications of the L-DACS2 system.

L-DACS2 signal characteristics
According to the L-DACS2 system definition proposal, the L-DACS2 is based on the Time Division Duplex (TDD) technique. Each transmission cycle lasts one second and is based on messages exchanges between a GS and a MS in its operational coverage. The information coming from the GS are

![Figure 4. DME interrogator screen for successful synchronization](image-url)
transmitted via the Forward Link (FL) and those from the MS via the Reverse Link (RL). An L-DACS2 frame is divided into five sections, as shown in figure 5. The three sections LoG2, CoS1 and CoS2 are used only by the MS (respectively for connection, signaling and data messages) whereas the two remaining sections UP1 and UP2 are employed only by the GS. Each section of the frame is composed by smaller transmission units called slots.

Figure 5. The L-DACS2 frame structure (reference [5])

The L-DACS2 communication is organized in five essential steps. First, the MS requests in LoG2 a connection to the serving GS. Second, the GS acknowledges this demand in the UP1 section of the next frame and allocates a slot to the MS for its signaling messages. In the third step, the MS indicates in the allocated slot (in CoS1) the number of needed slots to transmit its data messages (or sends a keep alive message if it does not have data messages to transmit). These slots are allocated by the GS in the UP2 section and finally used by the MS to transmit its data to the GS in CoS2.

In addition, the L-DACS2 system uses a 200 kHz transmission bandwidth and employs a Gaussian Minimum Shift Keying (GMSK) modulation. It is characterized by a 0.5 modulation index and a 0.3 BT product, where $T$ is the symbol duration ($T = 3.6923 \mu s$) and $B$ the 3 dB bandwidth.

In our scenario, we study on the effect of the onboard L-DACS2 interferer on the DME on board receiver. Thus, we focus on the signals sent by the MS. For the interfering signal, we only modify its modulation respecting the specifications of the L-DACS2 system.

The baseband signal

The baseband signal is represented by complex symbols stream, whose real and imaginary parts are respectively the In-phase and Quadrature data files.

We investigate four main types of modulations, which are often used in nowadays digital communication:

- **Minimum Shift Keying (MSK).**
- **Gaussian Minimum Shift Keying (GMSK).**
- **M-ary Phase Shift Keying (MPSK),** where $\log_2(M)$ is the number of bits per transmitted symbol.
- **M-ary Quadrature Amplitude Modulation (MQAM) where $\log_2(M)$ is the number of bits per transmitted symbol.**

MSK, GMSK and MPSK are constant envelop modulations (where the signal amplitude is constant irrespective of the phase variation) whereas MQAM is combined linear and constant envelop modulation (where both the amplitude and the phase of the signal vary from one symbol to another).

MSK is a special type of continuous phase-frequency shift keying where the peak frequency deviation between two consecutive symbols is the quarter of the symbol rate [10]. The baseband modulated signal is given by the equation:

$$s(t) = A(t) \exp(jh\pi\theta(t)),$$

Where $A(t) = A$ (constant) is the signal amplitude, $h$ its modulation index and $\theta$ its instantaneous phase:

$$\theta(t) = \theta_0 + i(t),$$

Where $\theta_0$ is the initial phase and $i(t)$ the instantaneous input symbols sequence. Its constellation is given by the figure 6 and the corresponding block diagram to create the MSK baseband signal is shown in figure 7.

Figure 6. MSK baseband signal constellation
GMSK is a derivative from MSK where the NRZ sequence is passed through a Gaussian filter. The constellation of such a signal is a constant-amplitude circle around the origin. We create the GMSK baseband signal following figure 8, starting from a Non Return to Zero (NRZ) sequence. The expression of the baseband modulated signal is similar to the MSK signal and its instantaneous phase is given by:

\[ \theta(t) = \theta_0 + g(t) \ast i(t), \]

\( \theta_0 \) being the initial phase and \( \ast \) the convolution between the input NRZ signal \( i(t) \) and the normalized modulating gaussian filter \( g(t) \) defined by the following equation:

\[ g(t) = \sqrt{\frac{2\pi}{\ln(2)}} BT \exp(-\frac{2(\pi BT)^2}{\ln(2)} t^2) \]

The corresponding block diagram is described more in details in [11]. It is based on information from [12] and it is summarized in figure 8:

**Figure 7. block diagram for MSK modulated baseband signal**

For the MPSK modulation, the baseband signal is defined by:

\[ s(t) = A(t) \exp(j\theta(t)) \]

The signal amplitude \( A(t) = A \) is constant and the instantaneous phase takes one of the values \( \theta_i = 2(i-1) \pi / M \), where \( i = 1, 2 \ldots M \). The I and Q data streams are given by the cosine and the sinus of the phase \( \theta \), respectively. As an example, we represent in figure 9 the constellation of the 16-PSK modulation.

**Figure 9. 16-PSK baseband signal constellation**

For the MQAM modulation, both the amplitude and the phase of the baseband signal vary with time. The coordinates \( (i, q) \) of each complex modulated symbol is an element of the matrix (where \( L^2 = M \)):

\[
\begin{pmatrix}
(-L+1, L-1) & (-L+3, L-1) & \ldots & (L-1, L-1) \\
(-L+1, L-3) & (-L+3, L-3) & \ldots & (L-1, L-3) \\
\vdots & \vdots & \ddots & \vdots \\
(-L+1, -L+1) & (-L+3, -L+1) & \ldots & (-L-1, -L+1)
\end{pmatrix}
\]

For example, we illustrate in figure 10 the 16-QAM constellation.

**Figure 10. 16-QAM baseband signal constellation**
Based on the mentioned information, we generated the normalized baseband interfering signal using Matlab tool. The average power of the modulated signal is unitary. The In-phase (I) and Quadrature (Q) data files are also created.

The RF signal

The second step of the interfering signal creation is its injection to the vectorial generator through specific software. For this, number of parameters should be taken into account:

- The sample clock of the RF signal (Hz)
- The carrier of the RF signal (Hz)
- The power of the RF signal (dBm)

The sample clock of the RF signal is the number of sampled symbols per second, i.e. the symbol rate. The symbol rate is determined by the time interval between two consecutive transmitted symbols. For the MSK, MPSK and MQAM modulations, the symbol rate is equal to the transmission bandwidth because there is no inter-symbol interference (one symbol is transmitted within the symbol period). Consequently, the sample clock is set to the specified L-DACS2 channel bandwidth, i.e. 200 kHz. For the GMSK modulation, the symbol rate is higher than the channel bandwidth because of the inter-symbol-interference. According to the specifications of the L-DACS2 system, the symbol rate is equal to 270 kbps (kilo bits per second). For our signal, we multiply this rate by the oversampling factor (which characterizes the digital to analog converter in figure 8) to obtain the sample clock.

In addition, the carrier of the RF signal is chosen such as the DME transponder and the L-DACS2 transmitter use the same center frequency (co-channel mode). In addition, the power of the RF signal is related to the L-DACS2 peak power, which depends on the desired SIR value. For our RFC analysis, the SIR is the ratio of the useful peak power (transmitted by the interrogator) over the interference peak power (transmitted by the generator). Finally, the L-DACS2 channel occupation rate is controlled by the “pulse” mode of the vectorial generator. This rate is given by the ratio of the pulse width over a reference period.

The aeronautical test-bed

To complete the interference scenario (see figure 3), we connect the obtained interfering signal (interference) to the two DME devices. The studied situation corresponds to RFC in the conducted mode. The unwanted signals are propagated through cables, connectors and imperfections of electronic devices.

We implement the RFC electrical circuit at the PTMS laboratory (“Plateforme Télécommunications Multi Services”) at Supélec. The test bed is shown in figure 11. It is composed by the commercial DME interrogator (the victim), the commercial DME transponder (useful transmitter) and the L-DACS2 generator (interferer).

We also introduced a combiner to add the interference signal to the useful one, and two circulators to enable the switching between the transmitting and the receiving functions of DME transceivers.

We added three spectrum analyzers to observe the spectra and the time domain form of the transmitted signals respectively at the output of the DME interrogator, the DME transponder and the combiner. Three directional couplers are introduced to connect each spectrum analyzer to the circuit.

In addition, according to the characteristics of the DME equipments, the transmit power range of the interrogator is close to 47 dBm. For this reason, we add an attenuator to protect the spectrum analyzer from the DME interrogator radiations. Because of the imperfections of the interrogator’s circulator, we introduce an isolator to protect the L-DACS2 generator (characterized by a maximum 10 dBm power input) from the radiations of the interrogator.

On the other hand, the transmit power of the DME transponder is lower than -47 dBm. Thus, it is optional to add low noise amplifiers to observe the useful signals.

To perform the study in the co-channel mode, the DME transponder and the L-DACS2 transmitter should use the same center frequency. The signal at the interrogator is completely determined once a channel is selected by the user. This channel determines the transmission frequency of both interrogator and transponder transmitted signals as well as the separation between the two peaks of a Gaussian shape [13].
RFC results: L-DACS2 over DME

Parameter settings

We first present the needed parameters to perform the RFC simulations. Based on the DME system specifications, we considered a maximum synchronization time of two seconds. In addition, we decided for the simulations to set the rate threshold of correctly received DME pairs to $\text{Rate}_{\text{min}} = 70\%$.

We carried out the simulations using Monte Carlo simulations on Matlab, and considering four situations for the DME interrogator: two different numbers of transmitted pairs per second (150 pulse pairs in the search mode and 30 pulse pairs in the track mode), and two different time intervals between the two pulses in a transmitted pair (12 microseconds in the X-mode or 36 microseconds in the Y-mode).

In addition, to perform the RFC measurements, we considered one DME channel. We also set the useful received power at the interrogator to -80 dBm, which is close to the receiver’s sensitivity (-83 dBm). Finally, we considered that the maximum synchronization time is two seconds, which means that the DME synchronization fails if two seconds after the start of the DME communication, the interrogator screen indicates none or inaccurate distance. To create the interference, we generated the L-DACS2 interfering signals based on the different modulations, starting from $10^5$ symbol sequences for the MPSK, MSK and MQAM modulations. For the GMSK modulation, we chose a 369 oversampling factor, with respect to the performance of the vectorial generator (maximum sample rate = 100 MHz). We chose four values for the SIR: 0 dB, -20 dB, -50 dB and -80 dB. For each value of the SIR, we determined the L-DACS2 channel occupation rate above which the DME synchronization is lost (after the synchronization time expires, the distance is not indicated at the screen of the DME interrogator).
**Simulation results**

Based on these parameter settings, Figure 12 illustrates the probability of DME synchronization success with respect to the L-DACS2 channel occupation rate for the four DME transmission modes. It shows that when the channel occupation rate is higher than 15%, the synchronization may fail for the search mode. For the track mode, where the DME stream becomes shorter in time, the synchronization failure may occur when the L-DACS2 channel occupation rate is higher than 30%. Based on the assumption that a DME pulse is lost when it overlaps with the L-DACS2 signal, the simulation results do not depend on the L-DACS2 modulation.

![Figure 12. Simulated DME synchronization success in the presence of the L-DACS2 interferer](image)

**Measurement results**

Table 1 illustrates the RFC result for different modulations based on the specification of the L-DACS2 candidate. We observe that the RFC is quite sensible to the modulation scheme employed at the interferer system, even if the modulations have similar spectra. The spectrum of a modulation (more precisely the occupied bandwidth) is the inverse of the symbol rate. Consequently, our MQAM, MPSK and MSK modulations have the same occupied bandwidth (200 kHz) and the GMSK a larger bandwidth (270 kHz).

<table>
<thead>
<tr>
<th>L-DACS2 modulation</th>
<th>SIR=0dB</th>
<th>SIR=-20dB</th>
<th>SIR=-50dB</th>
<th>SIR=-80dB</th>
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<td>BPSK</td>
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<td>70</td>
<td>67</td>
<td>66</td>
</tr>
<tr>
<td>QPSK</td>
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<tr>
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<td>GMSK</td>
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</table>
In general, we note that the modulation scheme can provide an increase of 5-10% of the acceptable L-DACS2 channel occupation rate, which would allow higher data rates. The higher channel occupation rate is, the larger the number of transmitted symbols within one second is.

We also notice that for the MQAM modulations of the L-DACS2 signal, the acceptable L-DACS2 channel occupation rate is constant with respect to the SIR and for all the tested values of M. This phenomenon might be related to the functioning of the DME receiver. For the MQAM modulation, the acceptable L-DACS2 channel occupation rate is near to 75%, which is very close to the result with the GMSK modulation.

We see that for a given SIR, the GMSK provides a very good performance and is one of the best schemes that we tested but higher M-ary modulations have a very close performance. However, even if the GMSK symbol rate is higher than the MQAM modulations, we could achieve a higher binary data-rate with 64-QAM comparing to the GMSK. In fact, we know that a GMSK modulated symbol corresponds to one bit whereas one MQAM modulated symbol corresponds to $\log_2(M)$ bits. On the other hand, the power of the GMSK signal is constant while it varies quickly with time for the 64-QAM because of the large number of constellation points and the transitions from one point to another among them.

For all the tested modulations of the interfering signal, we finally notice that in this precise aeronautical interference scenario, when the L-DACS2 channel occupation rate is lower than 66%, the DME synchronization remains successful for SIR values higher than -80 dB. Now, taking into account the specifications the L-DACS2 system, the maximal L-DACS2 channel occupation rate equals 6.7%. This corresponds to the longest L-DACS2 signal duration within one frame, where a connected MS uses the maximum allowed slots to transmit its signaling and data messages (more details about the L-DACS2 frame can be found in [12]). Hence, in the aeronautical environment presented herein and with the used commercial DME unit, the DME interrogator used in our aeronautical test-bed would not suffer from any penalty from the L-DACS2 interference if the SIR is higher than -80 dB, for all the tested interfering signal modulations.

Conclusion

In this paper, we studied the impact of an L-DACS2 transmitter on the DME system performance using a novel time domain approach. We performed the study in the co-site scenario (same airplane) and the co-channel case (simultaneous use of the same center frequency). We analyzed the effect of the L-DACS2 signal modulation on the results.

The simulations results that do not depend on the modulation show that for the specified L-DACS2 channel occupation rates, the L-DACS2 and DME do not collide within the analyzing time window.

We proved by measurements in our aeronautical test-bed that for all the L-DACS2 modulations, taking into account the time domain characteristics of both systems and according to these first experiments, the L-DACS2 would not cause harmful interference on the DME system with a SIR higher than at least -80 dB.

We also showed that the signal modulation has an effect on the measured RFC result and that the GMSK specified modulation has the best RFC results and provides 5 to 10% gain comparing to BPSK and QPSK modulations, in terms of acceptable L-DACS2 channel occupation rate. From these first results based on the interference of L-DACS2 with another system (DME), we noticed that high level modulations such as 64-QAM perform very close to the GMSK. However, deeper analysis is needed to compare these two modulations in terms of system performance (Symbol Error Rate, Binary Error Rate with respect of the Signal to Noise Ratio…).

The performed studies so far were carried out in the co-channel mode. To study more in details the effect of the L-DACS2 modulation on the RFC, further studies are needed in adjacent mode, where the interferer and the victim use close frequency channels at a given time slot.

These first measurements were obtained considering only one DME interrogator, one DME operational mode and one DME channel. Therefore, further studies are needed to improve and complement these results with other DME equipments and operating modes. In particular, additional metrics such as the distance precision will have to be considered. Moreover, in the precise environment presented in this paper, a good RFC level between L-DACS2 and DME is achieved.
because during a given time slot, only one of them transmits or receives signals. Actually, this condition will not be permanently satisfied as a large number of systems are implemented in the frequency band and also within the same airplane. As a result, these other systems should also be taken into account in the RFC study as well as some other effects including multipath, more detailed signal front end effect analysis and antenna coupling phenomena.

References

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