Bit Error Rate Validation for Aeronautical Communication System LDACS for Higher Modulation Schemes

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***Abstract*—The L-Band Digital Aeronautical Communication System (LDACS) is a new aeronautical communication standard between an aircraft and a ground station, which provides high data throughput with different modulation and channel coding schemes for reliable transmission. Conducted measurements of the LDACS receiver (RX) prototype have shown that the Bit Error Rate (BER) severely suffers for higher modulation schemes, while for lower modulation schemes, the results perfectly match with the stated ones in the LDACS standard. This paper evaluates the BER performance for all defined link types, modulation schemes, and channel types by simulations. As a matter of fact, some modulation and coding schemes defined in the LDACS standard show a strong degeneration of the BER for some channel types. Therefore, the different channel types are analyzed in this paper, and the pilot grid spacing is examined according to the underlying channel realizations regarding the phase variations of the channel by adjacent orthogonal frequency-division multiplexing (OFDM) symbols.**

***Index Terms*—aeronautical communication system, LDACS, bit error rate simulation, aeronautic channel model**

I. INTRODUCTION

The problem of nowadays European airspace is that it is highly congested for most parts of Europe. Future predictions claim that the air-traffic will increase by 50% worldwide in the next twenty years [1]. This trend is undoubtedly postponed due to COVID-19, but it can be expected a continuation of this trend when the crisis is over. The challenge is that today's communication systems are not capable of handling such an information increase. An additional data exchange can be expected, due to real-time adjustments of flight plans, e.g., by changing weather conditions [2].

As a matter of fact, the launch of a new system in the aeronautic L-band is not that simple because it is already used or reserved by legacy systems. The idea of LDACS is to place it between the existing navigation and surveillance systems as an overlay system without interfering with them. Unfortunately, the other way round is not true.

The main contributions of this paper are:

- Validation of BER for all defined LDACS channel models, modulation formats, coding schemes, and all link types. Although the LDACS system performance has been studied years ago [3]–[5], our research indicated performance problems with higher-order modulation schemes [6]. Investigating this, it became apparent that performance data for higher-order modulation schemes was analytically derived from QPSK simulations. Consequently, the effects of the challenging channel models have been overseen.
- Analysis of the underlying channel models and the pilot grid in time and frequency in regard to phase change of the channel between adjacent OFDM symbols.
- Recommendations for a more realistic channel behavior are given.

The organization of the paper is as follows. Section II gives an introduction to the LDACS system design. Furthermore, an overview of the implemented system simulator and the defined channel models is given in section III. The results of the conducted simulations will be presented in section IV, followed by further investigations of the channel models in section V.

II. LDACS SYSTEM DESIGN

TABLE I
LDACS SYSTEM PARAMETERS

Parameters	**Values**
Type	OFDM
Modulations	QPSK, 16QAM, 64QAM
max. Data Rate FL	$\approx 1.42\,\mathrm{Mbit/s}$
max. Data Rate RL	$\approx 1.1\,\mathrm{Mbit/s}$
Total Channel Bandwidth	$625\,\mathrm{kHz}$
Subcarriers	64 (50 used) $\Delta F = 9.765\,625\,\mathrm{kHz}$
Useful Symbol Duration T_U	$102.4\,\mathrm{\mu s}$
Cyclic Prefix Duration T_{CP}	$17.6\,\mathrm{\mu s}$
OFDM Symbol Duration T_S	$120\,\mathrm{\mu s}$
FL Frequency Band	$1110\,\mathrm{MHz} - 1156\,\mathrm{MHz}$
RL Frequency Band	$964\,\mathrm{MHz} - 1010\,\mathrm{MHz}$
SF periodicity	$240\,\mathrm{ms}$

LDACS is an OFDM-based, terrestrial, cellular communication system. It is part of a bigger project called Single European Sky Air Traffic Management Research (SESAR).

An LDACS Ground Station (GS) covers a cell radius of 200 NM, which corresponds to ≈370 km. All LDACS GS are synchronized with each other to provide a common time base for the link types. The communication from a GS to an Aircraft Station (AS) is called Forward Link (FL). The link is frame-based and starts with the Broadcast Channel (BC), comprising system identification of the current GS and information about the neighboring cells. The BC is followed by four Multi-Frames, containing data and control information for registered AS. The communication from an AS to a GS is called Reverse Link (RL). The RL starts with the Random Access (RA) channel, which gives an AS the opportunity to register itself to the communication system, e.g., when entering the European airspace. After the RA, four Multi-Frames follow with control and user data from each registered AS. For the RL, the subcarriers of an OFDM symbol are split into two halves, which is called RL tile. Depending on the required data exchange and cell utilization, an AS occupies one or more RL tiles. Both links have the so-called Super-Frame (SF) as the smallest common frame type, depicted in Fig. 1. The most relevant LDACS system parameters can be found in Table I, or in detail in the LDACS specification [6].

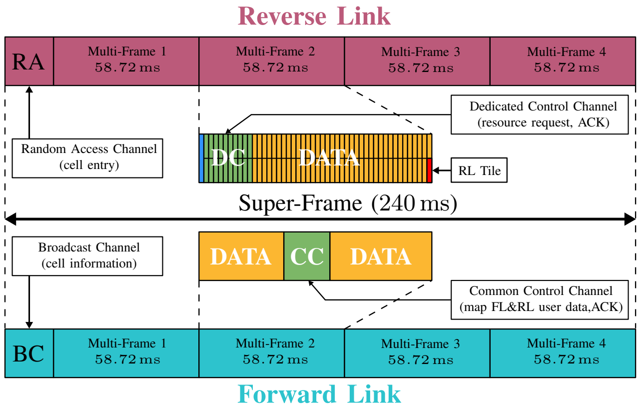


Fig. 1. FL and RL framing structure

III. Simulation Environment

This section gives an overview of the system simulator implemented in *MATLAB* and the defined channel types for LDACS.

A. LDACS System Simulator

With the simulator, it is possible to conduct FL, RL as well as RA simulations according to the LDACS standard [6]. The simulator consists of three parts, depicted in Fig. 2.

The first part is the transmitter, which supports all defined modulation schemes, and furthermore, the possibility to activate and deactivate the different coding schemes and interleaver. The smallest simulated frame type is one SF for the selected link type, including its different sub-frames. The simulator allows an additional fractional temporal offset of the simulated SF to verify the influence of an unsynchronized system.

The second part contains the defined channel models (see chapter III-B). The simulator offers the possibility to adjust the different channel parameters, like the Doppler shift and temporal delay of the scatterer. For the RL case, each AS is simulated with its own channel to get a more realistic behavior. This allows simulating the influence of two (or more) AS using RL tiles next to each other, with different Doppler shifts or even completely different channel types.

The third part is the receiver. Optionally it is possible to add receiver hardware characteristics, e.g., its frequency response and blanking behavior. In the first step, time and frequency synchronization is performed, followed by the channel estimation. After demodulation, the received data is decoded according to the frame type and compared with the sent one to determine the BER.

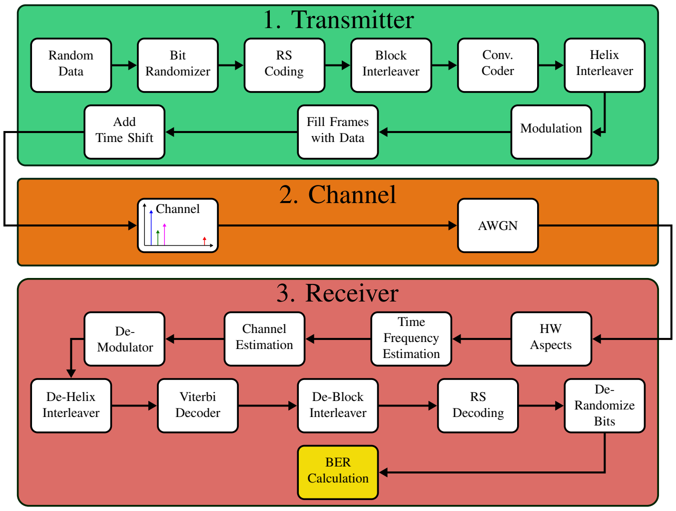


Fig. 2. Block diagram of LDACS system simulator

B. LDACS Channel Models

The channel models are presented in more detail because this will explain the worse simulation results and the exemplary channel realizations in sections IV and V. The channel models defined in the LDACS standard have undergone a long-lasting development. They have been adopted from former planed aeronautical communication systems, starting with the Broadband VHF (B-VHF) in the frequency range 118 MHz to 137 MHz. For B-VHF, various flight scenarios have been evaluated and analyzed. Those flight scenarios have been transformed into suitable channel models as a basis for a simulation environment [7]. The subsequent communication system to B-VHF was the Broadband Aeronautical Mobile Communication System (B-AMC), already planned for the L-band as an overlay system. Thus, the defined channel parameters from the B-VHF system have been adapted to the L-band [8]. LDACS is formed out of B-AMC but with different system and design parameters.

The LDACS standard defines three channel types (see Table II).

En-Route (ENR) channel: Represents an aircraft at its cruising altitude and speed. The channel shows a strong line-of-sight (LOS) component followed by a near specular component, resembling a ground reflection and a far-off specular, e.g., a mountainside. The Doppler spectrum for the scatterers is assumed to be Gaussian distributed.

Terminal Maneuvering Area (TMA) channel: Describes take-off and landing scenarios for an aircraft. For this channel, it is expected that an airplane has a dominant LOS component, and because of the lower flight level, uniformly distributed scatterer from the vicinity. The Power Delay Profile (PDP) shows an exponential decay of the scattering components, modeled as Rician fading process. Furthermore, the uniform distribution of the scatterers results in a Jakes type Doppler spectrum, with a strong Doppler shift for the LOS component.

Airport (APT) channel: Models taxiing and parking scenarios at the airport, where it is assumed that the AS is shadowed from the ground station. This non-line-of-sight (NLOS) channel uses a Rayleigh type fading model. The Doppler spectrum is of Jakes type since it is assumed that the airplane is uniformly surrounded by objects at the airport. All channel parameters for the corresponding channel types are listed in Table II.

TABLE II
CHANNEL PARAMETERS

Channel	Fading	Delay	Doppler
ENR	Rician: $k_{\mathrm{R}} = 15\,\mathrm{dB}$ near-specular to off-path: $k_{\mathrm{NS/OS}} = 6\,\mathrm{dB}$	$\tau_0 = 0.3\,\mu\mathrm{s}$ $\tau_1 = 15\,\mu\mathrm{s}$	$f_{\mathrm{D_{LOS}}} = 1700\,\mathrm{Hz}$ mean Doppler spec. $f_{\mathrm{M_0}} = 0.85 \cdot f_{\mathrm{D_{LOS}}}$ $f_{\mathrm{M_1}} = -0.6 \cdot f_{\mathrm{D_{LOS}}}$ Doppler spread spec. $f_{\mathrm{S_0}} = 0.05 \cdot f_{\mathrm{D_{LOS}}}$ $f_{\mathrm{S_1}} = 0.15 \cdot f_{\mathrm{D_{LOS}}}$
TMA	Rician: $k_{\mathrm{R}} = 10\,\mathrm{dB}$	exp. decay $\tau_{\max} = 10.5\,\mu\mathrm{s}$	$f_{\mathrm{D_{LOS}}} = 624\,\mathrm{Hz}$ Jakes spectrum for scatterer
APT	Rayleigh: $k_{\mathrm{R}} = -100\,\mathrm{dB}$	exp. decay $\tau_{\max} = 3\,\mu\mathrm{s}$	$f_{\mathrm{D}} = 413\,\mathrm{Hz}$ Jakes spectrum

IV. SIMULATION RESULTS

This section presents the BER simulations for FL and RL for all defined modulation and coding schemes [6]. Simulations are conducted for all presented channel types (see Section III-B). It is assumed that the received signal is perfectly synchronized, and the Doppler shift is exactly known to the receiver. Although LDACS is an overlay system, no interferer has been added to the simulations to get the system's true BER performance. The focus of the conducted BER simulation is primarily on user payload and not on the control and broadcast frames (see Fig. 1). One exception is the Dedicated Control (DC) frame, which consists of a single RL tile for each registered aircraft and has a weaker encoding compared to the defined user data simulations [6]. It represents the bottom limit for the RL BER performance. The maximum defined target BER defined by the LDACS standard is 10^{-6}.

A. Forward Link BER Simulation

The simulation results for the ENR channel depicted in Fig. 3(a) achieves the target BER, except for the weakest coding scheme for 64QAM.

For the TMA channel model, the BER is getting worse for some modulation and coding schemes. Simulations presented in Fig. 3(b) show that neither of the 64QAM coding schemes will be usable for approach and landing scenarios. Even for the 16QAM, only the most robust coding scheme shows good performance.

The APT channel simulations accomplish the target BER for all defined coding schemes for Quadrature Phase-Shift Keying (QPSK) and 16QAM modulations. For the 64QAM modulation, only the coding rate of $1/2$ fulfills the required BER below 10^{-6}. Coding rates $2/3$ and $3/4$ will not be usable for this channel type.

B. Reverse Link User Data BER Simulation

For RL user data simulations, it is assumed that two AS are registered to the system. Each AS uses one-half of each Multi-Frame and occupies as many adjacent RL tiles as possible. This procedure prevents the effect that two RL tiles from different AS affect each other in the time or frequency domain. Six Data tiles are jointly encoded according to the definition in the LDACS standard [6], otherwise the maximum possible tile count is used. Channel estimation is performed over adjacent RL tiles for the same AS.

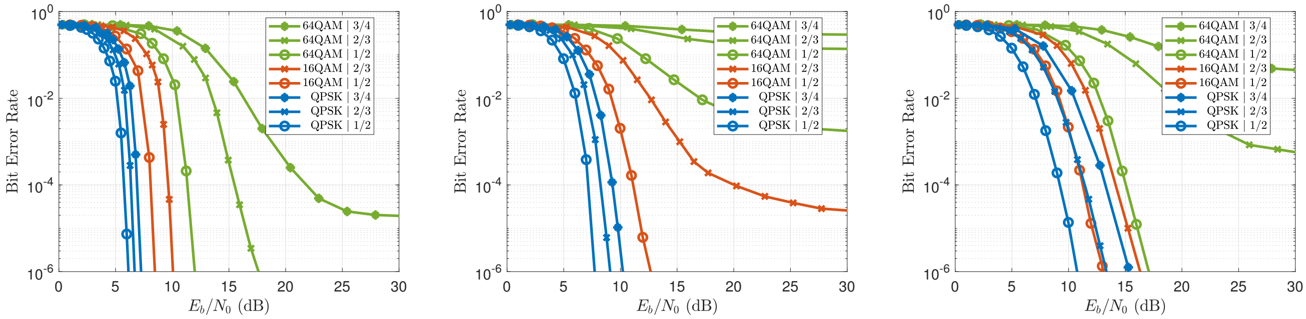
Fig. 4(a) depicts the simulation results for the ENR channel. All schemes work well except for the weakest two coding rates for the 64QAM modulation. The TMA (see Fig. 4(b)) and APT channel (see Fig. 4(c)) show the lowest BER performance. Both channels fulfill the target BER for QPSK with the coding rates $1/2$ and $2/3$. Additionally, the APT channel also attains the target BER for 16QAM with the strongest coding scheme.

C. Reverse Link DC Frame BER Simulation

The DC data has a fixed coding and modulation scheme, thus, the simulation results are presented over Signal-to-Noise Ratio (SNR). For DC simulations, channel estimation is performed independently for each DC frame since for each registered aircraft, one frame is allocated. Fig. 5 depicts the simulation results for all channel types. The DC data simulation shows severe BER problems for the TMA and APT channel, only the ENR channel achieves the required target BER.

D. Summary

The simulation results have shown that most of the QPSK modulation schemes work well for FL and RL user payload. The LDACS system design has severe problems for higher modulation schemes to fulfill the target BER of 10^{-6}. Especially the BER results for the DC frame needs further investigation. A similar problem occurred for RA simulations, with the effect that it is not possible to stay below the target BER for some channel types [9].

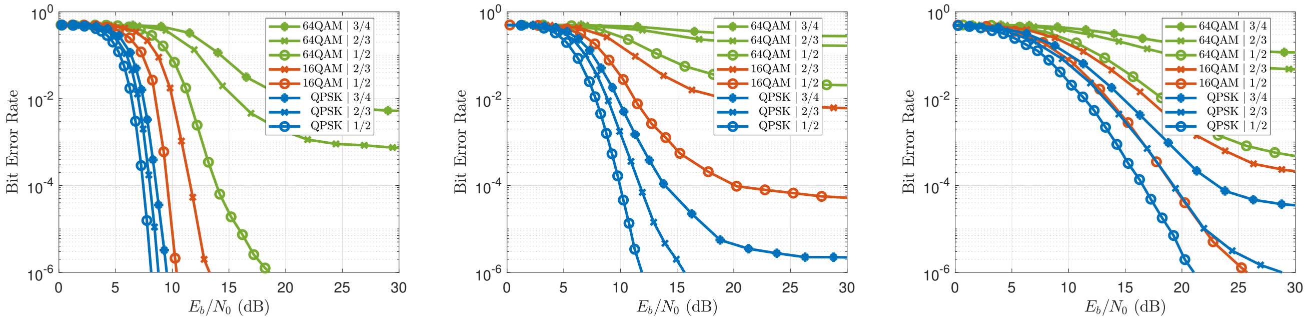


(a) ENR channel

(b) TMA channel

(c) APT channel

Fig. 3. BER simulation for Forward Link user data



(a) ENR channel

(b) TMA channel

(c) APT channel

Fig. 4. BER simulation for Reverse Link user data

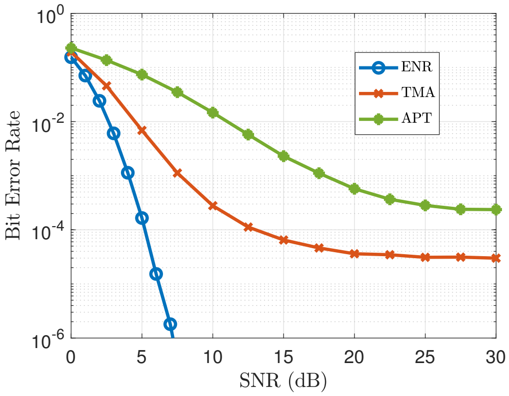


Fig. 5. BER simulation for Reverse Link DC frame for all channels

V. INVESTIGATION OF DEFINED CHANNEL MODELS

The conducted simulations show, independent of the link type, catastrophic BER results, especially for higher modulation schemes. Further investigations have shown that the channel models are the root cause for this effect.

This section gives an overview of the implemented channel models' behavior in the time/frequency domain. The presented plots in the following subsections display exemplary phase difference realization for each channel between adjacent OFDM symbols. The amplitude of the channel realizations shows strong variations as well, but for simplification, only the phase variation will be presented since no additional information is gained by adding the amplitude plots.

A. *ENR Channel*

The ENR channel depicted in Fig. 6 shows a strong periodicity of the phase difference along the frequency domain because of the strong far-off scatterer at $15\,\mu\mathrm{s}$, which translates into a $\approx 66.67\,\mathrm{kHz}$ component. The red dots in Fig. 6, 8 and 9 indicate the FL's pilot carriers and the green ones for the RL. The ripple along the carrier axis has a higher frequency compared to the pilot spacing, which violates the Nyquist-Shannon sampling theorem. This is exemplarily depicted for the FL pilot grid in the image detail Fig. 7. The dashed aid lines illustrate that the phase change of the channel between pilot carriers in the symbol direction is not covered. The resulting amplitude and phase error of the channel estimation lead to worse BER results, especially for higher modulation schemes because they are more sensitive to wrong predictions. Further investigations have shown that the used interpolation scheme for undersampled channel estimation has an impact on the BER. In this paper, the *MATLAB* function "griddata" with a natural-neighbor interpolation scheme is used, nevertheless, identifying the most suitable interpolation method for the undersampled channel is beyond the scope of this paper. Independent of the used channel estimation type, the target BER will not be achieved.

Scientific works provide a good starting point for a suitable pilot grid spacing [10]–[12]. The "rule of thumb" for the pilot grid in the time and frequency domain is given in (1) and (2). The calculation result for the ENR channel suggests a tighter pilot spacing along the time axis, which is not suited for a communication system with the goal of high data throughput. Unfortunately, (1) and (2) make general assumptions and do not take the channel parameters into account. That makes well-defined channel models and intensive simulations for a new communication system inevitable. An indication that the ENR channel is assumed too worse is the far-off specular component. Although reflected in a total distance of $\approx$4,500 m, it is only 21 dB less compared to the LOS component. Furthermore, the German Aerospace Center conducted flight trials showing that the far-off scatterer is about $\approx$41 dB lower than the LOS component [13], which results in a phase ripple below 2° in the frequency direction. Simulation results with the adapted channel model fulfill the target BER of 10^{-6} for both links. The BER plots are not depicted in the paper.

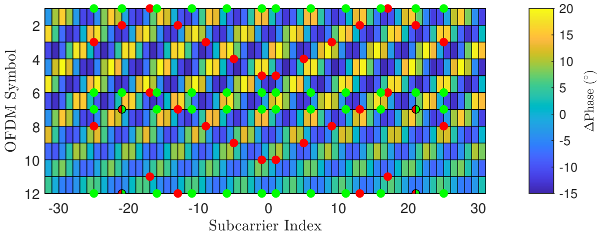


Fig. 6. Exemplary phase difference realization of ENR channel
🔴 FL pilot grid, 🟢 RL pilot grid

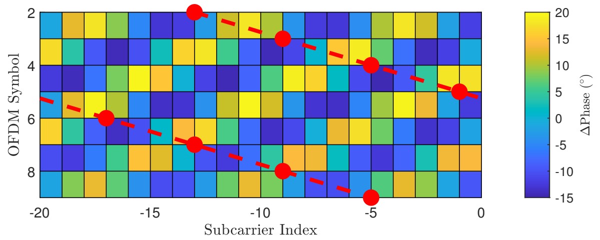


Fig. 7. Enlarged phase difference realization of ENR channel
🔴 FL pilot grid, - - - Aid line

$$\begin{aligned} N_t &\le \frac{1/2}{f_{D_{max}} \cdot T_s} \\ &\le \frac{1/2}{1700\,\mathrm{Hz} \cdot 120\,\mu\mathrm{s}} \approx 2.45 \end{aligned} \qquad (1)$$

$$\begin{aligned} N_f &\le \frac{1}{\Delta F \cdot \tau_{max}}, \tau_{max} = T_{CP} \\ &\le \frac{1}{9765.625\,\mathrm{Hz} \cdot 17.6\,\mu\mathrm{s}} \approx 5.81 \end{aligned} \qquad (2)$$

B. TMA Channel

The phase difference for adjacent OFDM symbols shows substantial phase variations along the time axis for the TMA channel, as depicted in Fig. 8. The phase differences are up to 40° and are not detectable for the underlying pilot grid. Those channel variations occur periodically, which leads to a worse BER performance. Literature search confirms that the assumption for the power delay profile matches quite well with measurements and the Doppler spread of $\approx$600 Hz [13], [14]. The maximum aircraft speed is assumed to be 10 m/s higher [15], but that has no relevant impact on the simulation results.

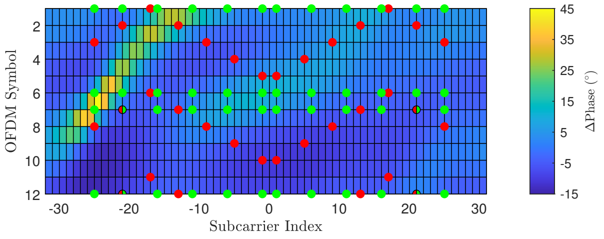


Fig. 8. Exemplary phase difference realization of TMA channel
🔴 FL pilot grid, 🟢 RL pilot grid

C. APT Channel

The strong channel variations for the APT are not detectable for the deployed pilot grid, as depicted in Fig. 9. For the APT scenario, the phase variations are even more substantial compared to the TMA case, by phase changes up to 50° between two adjacent OFDM symbols.

The reason is the unrealistic high Doppler shift for taxiing and parking of 413 Hz, which corresponds to an aircraft speed of $\approx$385 km/h. For this channel definition, it has to be clarified if it is part of the take-off and landing procedure, but even then, the typical take-off speed for a commercial aircraft is around 240 km/h – 285 km/h. Assuming the taxiing speed of 55 km/h [15], [16], the maximum Doppler would result in $\approx$60 Hz. By adapting the channel parameters, the FL fulfills the target BER for all modulation schemes. The same is true for the RL, except for the 64QAM with the coding rates $^2/_3$ and $^3/_4$.

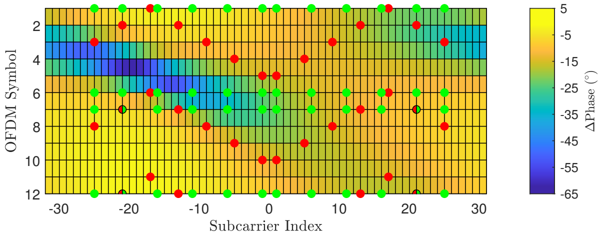


Fig. 9. Exemplary phase difference realization of APT channel
🔴 FL pilot grid, 🟢 RL pilot grid

VI. CONCLUSION

It has been shown that for the underlying LDACS channel models (section III-B), it is not possible to achieve the required BER of 10^{-6} [6] for higher modulation schemes. Especially the RL user data simulations show that only some coding schemes for the QPSK modulation are suitable for the TMA and APT channels. The BER simulation results for the DC frame are even worse. It reveals severe problems for the TMA and APT channels due to the strong phase variations for adjacent OFDM symbols, as shown in section V.

As stated in section III, the channel models have been designed and evaluated for B-VHF. Since this system was designated for a different frequency range and the channel models are the baseline for B-AMC respectively LDACS, it seems that the adaptation of the channel parameters has been assumed too worse. This has been confirmed as well by flight trials of the German Aerospace Center [13], but further investigations for a general validity are necessary.

If the defined channel models would be valid, adjustments to the pilot spacing will be necessary, as stated in section V-A. Also, the APT channel model's specific use has to be clarified since taxiing and parking with a speed of $\approx 385\,\mathrm{km/h}$ is not realistic. The LDACS consortium is informed about the BER simulation results and agrees that some assumptions regarding the channel parameters are too stringent and should be relaxed.

Further investigations have also shown that the used interpolation scheme for undersampled channel estimation influences the BER, depending on the channel and link type. The dependency of the underlying pilot pattern and channel type for the used interpolation scheme will be analyzed in the next step to identify the most suitable channel estimation scheme for LDACS.

ACKNOWLEDGMENT

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REFERENCES

[1] Eurocontrol, "European Aviation in 2040: Challenges of Growth; Annex1-Flight Forecast to 2040," Oct. 2018. [Online]. Available: https://www.eurocontrol.int/sites/default/files/2019-07/challenges-of-growth-2018-annex1_0.pdf

[2] SESAR, "4D Trajectory Managment PJ18 4DTM." [Online]. Available: https://www.sesarju.eu/index.php/projects/4dtm

[3] S. Brandes, U. Epple, S. Gligorevic, M. Schnell, B. Haindl, and M. Sajatovic, "Physical layer specification of the l-band digital aeronautical communications system (l-dacs1)." Crystal City, VA, USA: IEEE, 2009, pp. 1–12.

[4] U. Epple, F. Hoffmann, and M. Schnell, "Modeling DME interference impact on ldacs1," 2012.

[5] U. Epple, *OFDM receiver concept for the aeronautical communications system LDACS1 to cope with impulsive interference*, ser. Kommunikationstechnik. München: Verl. Dr. Hut, 2015.

[6] T. Gräupl, C. Rihacek, B. Haindl, and Q. Parrod, "LDACS A/G Specification," SESAR-JU, Tech. Rep. D3.3.010, December 2018.

[7] BAES, "D17 Software Implementation of Broadband VHF Channel Models, Rev. 2.0, Proj.Num.: AST3-CT-2003-502910," Tech. Rep., May 2006.

[8] German Aerospace Center, "D5 Deliverable: Expected B-AMC System Performance," Eurocontrol, Tech. Rep., Sep. 2007. [Online]. Available: https://www.eurocontrol.int/sites/default/files/2019-05/24092007-b-amc-project-deliverable-d5-v11.pdf

[9] Michael Zaisberger and Holger Arthaber, "Random Access Performance Evaluation and Improvements of the LDACS," *4th International Conference on Telecommunications and Communication Engineering, to be published*, 2020.

[10] R. Nilsson, O. Edfors, M. Sandell, and P. O. Borjesson, "An analysis of two-dimensional pilot-symbol assisted modulation for OFDM," in *Proc. IEEE Int. Conf. Personal Wireless Communications (Cat. No.97TH8338)*, Dec. 1997, pp. 71–74.

[11] P. Hoeher, S. Kaiser, and P. Robertson, "Two-dimensional pilot-symbol-aided channel estimation by Wiener filtering," in *Proc. and Signal Processing 1997 IEEE Int. Conf. Acoustics, Speech*, vol. 3, Apr. 1997, pp. 1845–1848 vol.3.

[12] M. Sandell and O. Edfors, *A comparative study of pilot-based channel estimators for wireless OFDM*. Luleå tekniska universitet, 1996.

[13] N. Schneckenburger, G. Galdo, U. Fiebig, and D. Matolak, *A Wide-Band Air-Ground Channel Model*. Dr. Hut, 2018. [Online]. Available: https://books.google.at/books?id=H1nGtQEACAAJ

[14] A. Skrzypczak, A. Thomas, and G. Duponchel, "Publisher international foundation for telemetering journal international telemetering conference proceedings rights," 10 2013.

[15] E. Haas, "Aeronautical channel modeling," *IEEE Transactions on Vehicular Technology*, vol. 51, no. 2, pp. 254–264, Mar. 2002.

[16] P. Pulini, S. Plass, L. Taponecco, M. Morelli, and L. Sanguinetti, "Aeromacs evolution - analysis during landing, take-off, and approach phases," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 50, 01 2013.