FEASIBILITY OF LDACS1 CELL PLANNING IN EUROPEAN AIRSPACE

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Abstract

The L-band Digital Aeronautical Communications System (LDACS) is the air-to-ground data link technology within the Future Communications Infrastructure (FCI). LDACS1 is one of two candidate LDACS technologies that have been recommended for further study by ICAO. In this paper, we assess the feasibility of a Europe-wide deployment of the LDACS1 system. For this purpose, we consider the estimated data traffic load for the year 2020, as well as twice the 2020 traffic load, and perform cell planning to serve this traffic with LDACS1 base stations. The requirement is that the proposed cell planning is able to fully serve the expected traffic and to provide full coverage of the continental European airspace above Flight Level 100. We propose a frequency assignment which takes into account the interference from Distance Measuring Equipment (DME) ground stations, which are also operating in the L-band. We come to the conclusion that a European deployment of LDACS1 is easily achievable, coexists well with today's operating DME stations and still leaves significant room for future traffic growth.

Introduction

The L-band Digital Aeronautical Communications System (LDACS) is the air-to-ground data link technology within the Future Communications Infrastructure (FCI). Jointly developed by Eurocontrol and the Federal Aviation Administration (FAA), the FCI comprises current and future communications technologies, which are required to implement the modernization of Air-Traffic Management (ATM) as currently pursued within SESAR [1] and NextGen [2] in Europe and the US, respectively.

Two candidate systems for LDACS have been selected from a rich variety of proposals and the ICAO recommended to further investigate both systems in detail. LDACS1 is the broadband candidate technology for LDACS and employs Orthogonal Frequency-Division Multiplexing (OFDM) as modulation. It is designed as a frequency-division duplex (FDD) system. LDACS2 is a narrowband single-carrier system utilizing time-division (TDD) as duplex scheme. In the remainder of this paper, we will concentrate on LDACS1.

LDACS1 is intended to operate in the aeronautical part of the L-band (960-1164 MHz). 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 military Joint Tactical Information Distribution System (JTIDS). Several fixed channels are allocated for the Universal Access Transceiver (UAT) at 978 MHz and for Secondary Surveillance Radar (SSR)/Traffic Collision Avoidance System (TCAS) at 1030 and 1090 MHz.

Due to these systems, free spectral resources are scarce and difficult to allocate in the aeronautical part of the L-band. To provide a sufficiently high capacity for current and future ATM applications, LDACS1 pursues the approach to make use of the gaps between adjacent DME channels. Of course, the design of the physical layer also allows deploying LDACS1 in unused parts of the L-band.

In this paper, we address the question "Is a deployment of LDACS1 on a European scale feasible?" Answering this question requires a detailed network planning procedure, taking into account both the geographic distribution of the expected future data traffic load, as well as the effects of interference from other systems and between LDACS1 cells.

This work represents the first detailed network planning effort for LDACS1. A similar frequency planning task has been performed in [3] for B-AMC, a predecessor of the LDACS1 system. Since B-AMC is a predecessor of LDACS1, the approach in [3] could also be applied to LDACS1 with minor changes. However, our approach here is more detailed in that it considers the data traffic load that will need to be handled by the network and also considers the effects of DME interference on the Bit Error Rate (BER) of the LDACS1 physical layer.

The remainder of this paper is organized as follows: We first present a brief overview of the LDACS1 system, focusing on the possible spectral deployment scenarios in the L-band. We then introduce our network planning approach. First, we describe our model for the air and data traffic. Then, we propose a cell planning algorithm that decides where LDACS1 cells should be located and what range each of these cells should have, based on the previously generated traffic load. We discuss the results of this cell planning step. Then, we propose a frequency planning algorithm that assigns a channel to each of these cells, taking DME and LDACS1 co-channel interference into account. Finally, we present frequency planning results for two different deployment scenarios for LDACS1 in the L-band.

Overview of LDACS1

In this section, we will give a brief overview of the LDACS1 system. For more detailed information please refer to the LDACS1 system specification [4], [5].

LDACS1 is intended to operate in the lower part of the L-band (960-1164 MHz). It is designed as a frequency division duplex (FDD) system, which enables a Ground Station (GS) to transmit continuously at a certain frequency on the Forward Link (FL), while the Airborne Station (AS) transmits at the same time but at a different frequency on the Reverse Link (RL). To allow the wireless channel to be used as efficiently as possible, LDACS1 supports adaptive coding and modulation on both the FL and the RL. Eight different coding and modulation schemes have been defined for the FL and the RL, allowing the data rate of each user to be adapted to the channel conditions. Depending on the coding and modulation scheme used, the data rate varies between approx. 303 and 1373 kbps on the FL and 220 and 1038 kbps on the RL.

For the deployment of LDACS1 in the L-band, two different scenarios are possible[1]: the inlay and the non-inlay scenario. Both of these scenarios will be explained below. Note that the LDACS1 specification currently does not mandate any particular deployment scenario, either for the location of the FL and RL channels in the spectrum, or for the duplex spacing between paired FL and RL channels.

The most preferable but also 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. This approach allows an LDACS1 deployment without changing existing DME assignments. For the inlay scenario, the LDACS1 specification proposes to use the frequency range from 985.5 to 1008.5 MHz, whereas the RL channels should be placed in the frequency range from 1048.5 to 1071.5 MHz. This spectral deployment keeps sufficient guard bands to the other L-band systems, SSR Mode S, and UAT, and is illustrated in Figure 1. Regions in which both DME Interrogation (air to ground) and Reply (ground to air) channels are active are shown in dark green, regions with Reply channels only are shown in lighter green. It can be seen that the LDACS1 FL channels are only affected by interference from DME Reply Channels. This allocation would provide a total of 24 channels.

The non-inlay scenario foresees the use of LDACS1 in regions of the spectrum where no DMEs are active. No details of a non-inlay deployment are provided in the specification. In principle, two different non-inlay approaches are possible. Either LDACS1 is deployed in the small regions of the L-band that are currently not used by DME's, or the current DME assignments are reorganized in order to create free spectrum for a non-inlay LDACS1 deployment. Of these two possibilities, we will concentrate on a non-inlay deployment in those parts of the L-band that are currently not used by DME's. Our proposal for a non-inlay scenario is described in the following. The region from 960.5 MHz to 970.5 MHz at the very bottom of the aeronautical L-band would provide 11 FL channels. Although national

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[1] A third option, the so-called overlay scenario, in which LDACS1 ground stations operate at the same frequencies as the DME ground stations, is not considered here.

DME allocations are possible in this region, this band is practically free of DMEs. A guard band of 7 MHz is left to UAT at 978 MHz, as in the inlay scenario. The RL channels could be located at a frequency offset of 193 MHz, at the very top of the aeronautical L-band. In this region, only DME reply channels are active. By locating LDACS1 ground station receivers sufficiently far away from DME ground stations, DME interference in the RL would also be avoided completely. This deployment option is shown in Figure 2.

Of course, combining both the inlay and non-inlay scenarios would also be possible, providing a total of 35 channels. Further channels could be gained by using the spectrum around 978 MHz as well, which has been kept clear in both deployment options here because of the use by UAT.

LDACS1 is designed to be deployed as a cellular network. In this case, the available channels will be reused in cells that are spaced sufficiently far apart as to keep the co-channel interference from other LDACS1 cells within tolerable levels. The LDACS1 link budget specifies a minimum carrier to noise ratio of 5.2 dB in the en-route domain in the presence of DME interference in order to maintain a BER below the target of $1 \cdot 10^{-6}$. The co-channel interference from other LDACS1 cells is assumed to contribute to the noise power. Obviously, careful network planning is necessary in order to minimize both DME interference and co-channel interference. This topic will be addressed in the rest of this paper.

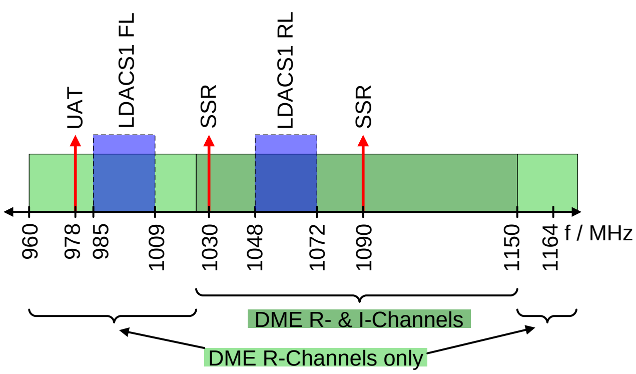

Figure 1. Inlay option for spectral deployment of LDACS1

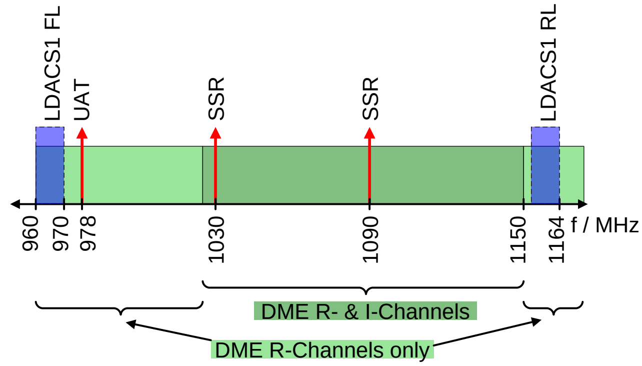

Figure 2. Non-Inlay option for spectral deployment of LDACS1

Overview of Network Planning Approach

In this section, we will give an overview of our network planning methodology. In the following sections, each of the steps will be discussed in detail. We have split the network planning problem into two sub-problems.

First, we address the cell planning problem, i.e. deciding where cells should be located and what their cell radius should be. This cell planning step requires a realistic model of the geographical distribution of the amount of data traffic that will need to be handled by the LDACS1 network. This traffic load model is generated from a realistic air traffic model and an application model that is based on the Communications Operating Concept and Requirements (COCR) document [6] that has been produced jointly by Eurocontrol and FAA. The main goals of the cell planning step are to cover the entire traffic load and to provide complete coverage of the continental European airspace above FL 100.

In a second step, this cell layout is used as input for the frequency planning. Here, LDACS1 channels are assigned to the cells. Since the expected traffic volume on the FL is much higher than on the RL, we focus on the allocation of FL channels only. Although the LDACS1 specification suggests that the offset between FL and RL channel frequencies should be constant for all cells, this need not necessarily be the case. In principle, the RL channels can also be assigned completely independently of the FL channels. The main sources of interference on the LDACS1 FL are DME ground stations. This interference has been characterized by Epple *et al.* in previous work [7]. The results from [7] tell us for every LDACS1 channel in the range from 985.5 MHz to 1008.5 MHz where in Europe this channel can be used, and where the interference from the DMEs would be too high, so that the channel cannot be used reliably. This allows us to determine the set of candidate channels for every cell. The second major source of interference that must be considered in the frequency planning step is co-channel interference from other LDACS1 ground stations transmitting on the same channel. We propose a frequency planning algorithm that allocates each cell one of its candidate FL channels, while making sure that co-channel interference from other LDACS1 cells on the same channel is kept low enough to guarantee a BER below $1 \cdot 10^{-6}$.

In our work, we do not consider the effect of terrain on the propagation of radio waves. Due to shadowing effects, a larger number of cells may be required to achieve the same coverage if a terrain model is included. On the other hand, hilly or mountainous terrain could also be used to an advantage in the frequency planning step, since it can limit the range at which an LDACS1 cell can interfere with another cell on the same channel. Such investigations are left for future work.

It is important to note that our proposed cell and frequency planning is not optimum in any sense. We do not aim to find the minimum number of ground stations that will be required in a Europe-wide LDACS1 network. Rather, we intend to show the feasibility of such a network.

Traffic Load Modeling

The generation of realistic traffic load for the LDACS1 network is based on two main components: an air traffic model that provides us with the distribution of aircraft in the European airspace, and a data traffic model that determines how much data traffic is generated by each aircraft, depending on its current flight situation. Our approach for modeling these two aspects is discussed below.

Our air traffic model is based on an IATA database of scheduled flights worldwide, including both passenger and cargo flights. This data is available from Innovata LLC [8]. Our database contains all scheduled flights on May 21-22, 2007. These days can be considered to be typical days, in that they do not exhibit a particularly high or low amount of traffic. We have analyzed this file in order to create a statistical model of the European air traffic patterns. For each hour of the day, the number of flights between any two airports was recorded, giving us an hourly aircraft generation rate for each airport, depending on the time of day.

Since we are focusing on European traffic only, we have limited our analysis to the region between 35° N and 60° N and 10° W and 30° E. This region will be referred to as the Region of Interest (ROI) in the remainder of this paper. Along the boundary of this spherical rectangle, virtual airports were created, and flights entering or leaving European airspace were mapped to the virtual airport that is closest to the aircraft's point of intersection with the boundary.

The resulting aircraft generation rates for both the real and virtual airports allow us to generate realistic amounts of air traffic in European airspace. Simulations representing the busiest traffic hour have been run for durations significantly longer than only one hour, in order to gain statistically meaningful results. To scale the air traffic volume to future scenarios, the aircraft generation rates are scaled according to predictions of the growth of air traffic in the future. Such studies are regularly published by Eurocontrol STATFOR [9]. For this work, we have scaled the traffic according to the High Growth scenario of STATFOR's 2010 Long Term Forecast [10] to the year 2020. With the flight database from 2007 as a baseline, this corresponds to an increase by the factor 1.49.

The route that is flown by an aircraft from its departure airport to its destination can either be chosen as the great circle route directly connecting the two airports, or a shortest path routing along actual navigational waypoints can be calculated. In either case, the aircraft velocity is chosen to match the flight duration resulting from the departure and arrival times specified in the original IATA flight database.

The data traffic model is based on the definition of applications in the COCR. This document defines a number of Air Traffic Control (ATC) and Airline Operational Communications (AOC) applications that are expected to come into service in the future.

Such applications can be triggered either periodically, on a domain basis, e.g. once per arrival, or on a per sector basis, e.g. clearances that are issued by an ATC controller. For each application, COCR defines how often the application is triggered, how many messages are exchanged between the aircraft and the ground system, what the sizes of these messages are, and what the quality of service requirements of the application are. We have implemented the COCR applications in our simulation environment according to these parameters.

However, not all applications listed in the COCR are relevant for the LDACS1 system. For example, the SURV application, a surveillance service, will likely use a dedicated data link such as Extended Squitter. Services such as D-TAXI, which are used only on the airport surface, have not been considered, since these will likely also make use of a dedicated airport data link such as AeroMACS [11] instead of LDACS1.[2] COCR distinguishes between two phases in the introduction of data link services. In Phase 1, voice is still the primary means of communication, and data link merely plays a supporting role. In Phase 2, data has replaced voice as the primary means of communication, but voice is still retained as a fallback solution. Here, we consider only Phase 2, since this is the much more challenging environment in terms of data load and latency requirements.

The COCR message sizes already include overhead due to network protocols, integrity, and security. For each application layer message that is received either on the ground or at the aircraft, a transport layer acknowledgement is sent back to the sender. The size of this acknowledgement is constant at 60 Bytes, corresponding to an IPv6 header of 40 Bytes plus a TCP header of 20 Bytes.

With our implementation of the COCR applications, combined with the air traffic model discussed previously, we have created a Load Map of the region that we are investigating. The Region of Interest was divided into 2000 rectangular bins of size 0.5° in longitude and 1° in latitude. Then, air traffic was generated according to our model, scaled to the year 2020, and the resulting data traffic was simulated. It was assumed that all aircraft are equipped with LDACS1 capability.

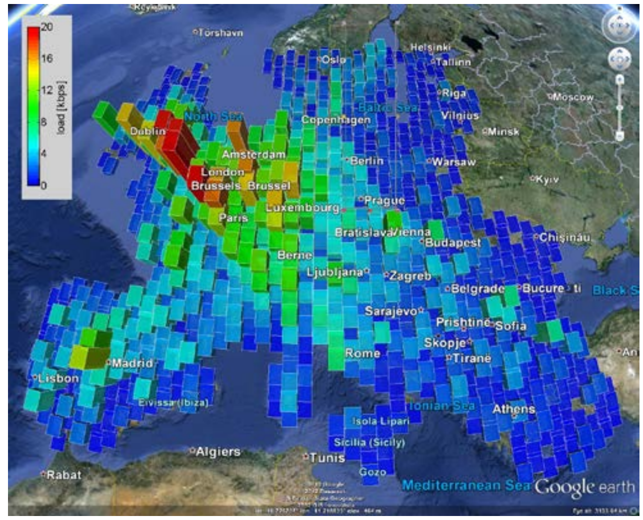

Figure 3. FL load map

For each bin, the average traffic in kilobits per second generated on the FL and the RL was determined. The resulting distribution of the FL data traffic load is shown in Figure 3. This load map is the basis of the LDACS1 cell planning, which will be discussed in the following section. The total traffic load generated within our ROI is approx. 2087 kbps on the FL and 551 kbps on the RL. The total number of aircraft in the ROI in steady state is approx. 3013.

A similar analysis of the total data traffic generated in European airspace has been previously carried out by Rokitansky *et al.* in [12] for the capacity assessment of the proposed Iris satellite communications system. Although the underlying assumptions in [12] are slightly different, it is worthwhile to compare the results therein to ours. Rokitansky *et al.* arrive at a total number of 4788 aircraft in the TMA and ENR domains generating an average load of approx. 3755 kbps on the FL and 699 kbps on the RL.

The higher load reported in [12] can be attributed in part to a larger assumed increase in the air traffic of about 1.76, as compared to 2007. This assumption was based on the older Long Term

[2] The complete list of simulated applications is: ACL, ACM, ARMAND, C&P ACL, COTRAC, D-ATIS, DLL, D-ORIS, D-OTIs, D-RVR, DSC, D-SIG, D-SIGMET, DYNAV, FLIPCY, FLIPINT, ITP ACL, M&S ACL, PAIRAPP ACL, PPD, SAP, WAKE, AOCDLL, ENGINE, FLTPLAN, FLTSTAT, FREETXT, FUEL, GATES, LOADSHT, MAINTPR, MAINTRT, NOTAM, POSRPT, WXGRAPH, WXRT, WXTEXT, NETCONN, NETKEEP.

Forecast from 2006. Another difference between our traffic model and the model of [12] is that [12] considers the European Civil Aviation Conference (ECAC) area, which is slightly larger than the rectangular region we are considering. Also, the traffic load in [11] includes both traffic over land and water, since it is intended for the capacity assessment of a satellite system, whereas we only consider traffic over land areas.

Cell Planning Algorithm

The task of cell planning is to decide where LDACS1 cells should be located, and what their cell sizes should be. Naturally, it is desirable to design a network with as few base stations, or cells, as possible, in order to minimize the costs of deployment. Our cell planning addresses three goals:

1. Complete coverage of the airspace above Flight Level (FL) 100,
2. Coverage of 100% of the traffic demand according to the load map,
3. No cell shall be overloaded.

The first requirement can be converted into a maximum permissible range of the ground stations. Aircraft that are flying at FL 100, i.e. an altitude h = 3048 m, and are further away from the ground station than this maximum range are no longer within the radio horizon of the ground station. Then, the maximum radius of a cell is given as

$$r_{\max} = \tilde{R}_E \cdot \cos^{-1}\left(\frac{\tilde{R}_E}{\tilde{R}_E + h}\right).$$

When $\tilde{R}_E = \frac{4}{3} R_E$ is the Earth radius, scaled by a factor to account for refraction in the atmosphere [13], and h = 3048 m, i.e. FL 100, we have $r_{\max}$ = 228 km, or 123 nmi. This is slightly larger than the maximum range of 120 nmi for en route cells as foreseen by the LDACS1 specification. Therefore, if all of the traffic load is covered by cells with ranges of at most 120 nmi, the coverage requirement above FL 100 is fulfilled inherently.

For the second requirement, it is important to note that the load map only includes traffic load over land areas. Therefore, we do not have to deal with the case that traffic load cannot be covered because it is too far away from a potential ground station site.

For the third requirement, we feel confident that an LDACS1 cell can easily handle 300 kbps, since this is the rate that is achievable with the most robust coding and modulation scheme. With larger modulation alphabets and higher code rates, higher data rates can be achieved. Since the amount of traffic generated in the FL is significantly higher than the traffic in the RL, but the capacity of LDACS1 is symmetric, only the FL is considered for this requirement.

To solve the cell planning problem, we define a greedy iterative algorithm which adds a new cell in every step, until the target coverage is reached. The algorithm maintains a set of active and a set of inactive cells. Initially, the set of active cells is empty, and the set of inactive cells contains the locations of all major European airports. This list is extracted from the EUROCONTROL Skyview tool [14] and comprises a total of 1027 locations. In principle, in each step, an entry from the set of inactive cells is moved to the active cells. This entry is chosen such that the total traffic load covered by all active cells is maximized. However, this simple greedy approach has one drawback: It avoids overlapping coverage areas of the cells, since any overlap would reduce the amount of load that is covered. This will lead to gaps between cells, which would need to be filled in by a large number of cells later on, when no large uncovered areas remain. Therefore, when deciding which cell to activate, we do not consider the entire set of inactive cells. Instead, we consider the set of N cells that would lead to the largest increase in total covered traffic load. Setting N to 50 appears to provide good results in practice. From this reduced set, the cell is activated that is closest to the geographic center of all currently active cells. This will lead to a slight overlap between activated cells, ultimately reducing the total number of cells that are required. The range of the newly added cell is then adjusted such that it is as large as possible without exceeding the cell's capacity limit. If the capacity limit is not reached, the cell range is limited to 120 nmi, to assure coverage above FL 100 as calculated above.

This procedure of moving cells from the set of inactive cells to the set of active cells is repeated until the target percentage of the total traffic load has been covered. According to the requirements that we formulated above, this target should be 100%. However, it may also be of interest to halt the algorithm before full coverage is reached, e.g. to determine the number of ground stations that are required to achieve a certain coverage. After the algorithm terminates, there may be significant overlap between neighboring cells. Therefore, the range of each cell is reduced as much as possible without introducing any holes in the coverage. Reducing the cell radius facilitates the frequency planning step, since smaller cells are less susceptible to interference. If the radius of any cell can be reduced to zero, this cell is removed from the set of active cells.

Of course, it is possible to place all cells in the manner described above. However, it appears plausible that large airports will deploy LDACS1 ground stations relatively early on. Therefore, we do not start with an empty set of active ground stations, but initialize this set to the locations of the largest European airports. The number of airports in this set is varied as a parameter in our simulations.

Cell Planning Results

To assess the results of our cell planning algorithm, we use the traffic load that is generated when the number of flights is scaled to the year 2020. It is interesting to first look at the number of cells that are required to cover a certain percentage of the total load in the load map. This relationship is shown in Figure 4.

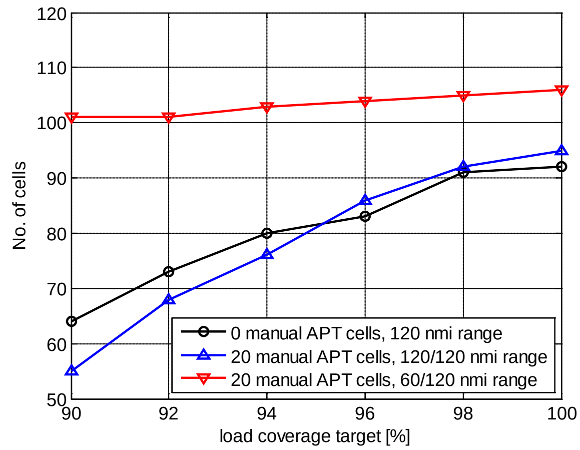

Figure 4. Number of LDACS1 cells required to reach different degrees of load coverage

Several different cases are considered: The black line represents the case that no cells are manually placed at any sites initially. The maximum range of all cells is 120 nmi, corresponding to the maximum LDACS1 cell radius according to the specification. The blue line represents the case that 20 cells are initially placed at the 20 largest European airports[3]. The maximum range of all cells is still set to 120 nmi. This scenario will be referred to as the “120/120 nmi scenario”. Finally, the red line represents the case that the range of the 20 initial airport cells is restricted to only 60 nmi. This case will be referred to as the “60/120 nmi scenario”. Not surprisingly, the number of cells required increases with the target load coverage percentage. Initializing the algorithm’s active cell set to the top 20 airports slightly reduces the total number of cells required when the target coverage is relatively low. This is due to the fact that most of the traffic load is located near these airports. However, this gain is lost when the target percentage is increased. Limiting the cell radius of the airport cells to 60 nmi significantly increases the total number of cells that are required. This is caused by the gaps that are left between these relatively small cells, which need to be filled in with additional cells

[3] This ranking is based on the number of passengers in the year 2011. The list is: London Heathrow, Paris Charles de Gaulle, Frankfurt, Amsterdam, Madrid, Munich, Rome, Istanbul, Barcelona, London Gatwick, Paris Orly, Zurich, Palma de Mallorca, Copenhagen, Vienna, Oslo, Düsseldorf, Milan, Stockholm, Manchester.

by the cell planning algorithm in order to reach the targeted coverage.

The total number of cells required to cover the entire traffic load is 92 without manual initialization of any cells, 95 with the 20 manually placed cells and 120 nmi range, and 106 when the maximum range of the manually placed cells is reduced to 60 nmi. In the following, we will focus on these last two cases, i.e. 100% coverage with 20 cells manually placed at the largest airports.

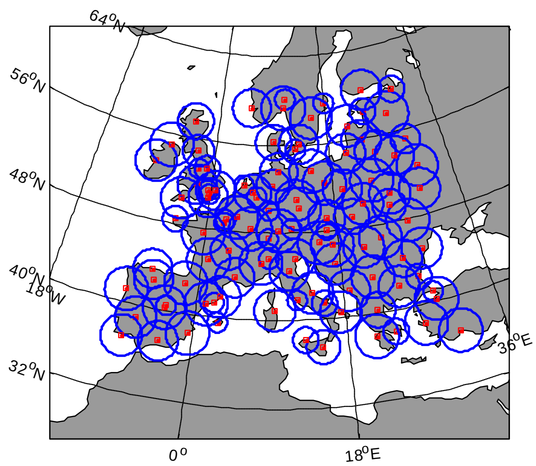

Figure 5. Cell planning results for 60/120 nmi scenario

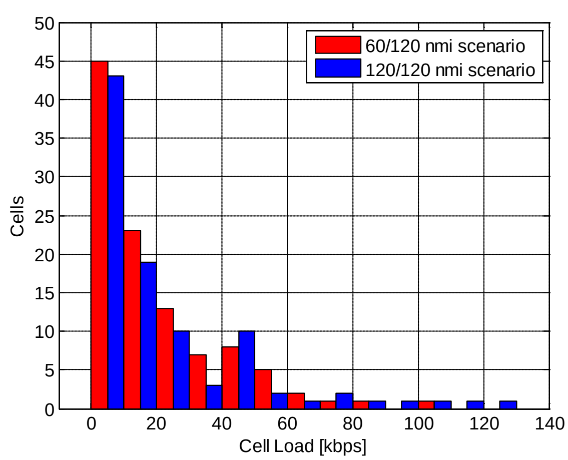

Figure 6. Traffic load distribution of LDACS1 cells

Figure 5 shows the geographical locations and cell sizes of all 106 cells in the 60/120 nmi scenario. The maximum cell load in this case is 102.5 kbps. This value is reached by a cell located near Nancy, France. However, as seen in Figure 6, the load distribution of the cells resembles an exponential distribution, with an average cell load of only 19.7 kbps in the 60/120 nmi scenario. This result underlines that the critical factor for the cell planning are not the cells' capacity constraints, but rather the coverage constraints. The traffic load distribution in the 120/120 nmi scenario is also shown in Figure 6. Here, the maximum cell load is slightly higher, at 125 kbps. This load is achieved by the cell located at Frankfurt. The load of this cell has increased with respect to the 60/120 nmi case due to the larger cell radius of the initial airport cells.

We have also executed the cell planning algorithm with twice the data traffic load of the 2020 scenario. This would correspond to the traffic that is generated around the year 2035, assuming that the air traffic continues to grow exponentially at the same rate as between 2007 and 2020, i.e. about 3.9% annually. We observed that the output of our cell planning algorithm remains the same, i.e. the number of cells that are required does not increase, because the cells still have sufficient spare capacity.

Frequency Planning

After the locations and transmit ranges of the LDACS1 ground stations have been decided, we must allocate an FL channel and an RL channel to each station. Since the FL allocation is much more critical due to the higher traffic load on the FL, we will consider frequency planning for the FL only. The LDACS1 specification suggests, but does not mandate, a constant frequency offset between FL and RL channels of a cell in order to simplify hardware implementations. In this case, the RL allocation would be determined by the FL allocations.

The frequency planning step is crucial for our analysis. If a feasible allocation of channels to cells can be found, this means that LDACS1 can indeed be successfully deployed on a European scale. On the other hand, if a feasible allocation cannot be found, this does not necessarily imply that a solution does not exist. In such a case, it may be necessary to apply a more sophisticated approach to the network planning problem. For example, the steps of cell planning and frequency planning could be addressed jointly, in order to avoid difficult interference constellations from the beginning.

Interference Modeling

Since the L-band is also used by other radio systems, LDACS1 channels are subject to interference. The level of this interference depends on the geographic location and the channel that is used. In previous work [15], it has been shown that the interference from DME ground stations to the LDACS1 FL is the most severe. For the frequency planning, we make use of the results presented in [7]. Since the positions and channel allocations of DME ground stations are known, and DME ground stations transmit at a constant pulse rate, the interference caused by the DMEs can easily be determined. This interference is characterized in [7] in terms of pulse rates and pulse powers. Based on simulations of the LDACS1 physical layer, a method is then derived that allows this characterization of the DME interference to be converted into the resulting BER that will be experienced on the LDACS1 FL. An interference map is created, dividing European airspace up into small bins of size 1° of longitude by 0.5° of latitude, as in the case of the load map used in this paper. For each of these bins, it is determined which LDACS1 channels will be able to operate reliably, i.e. at a BER below $1\cdot10^{-6}$. Since this depends on the Signal to Noise Ratio (SNR) at the AS (Airborne Station), values of the SNR between 3.2 dB and 5.2 dB in steps of 0.5 dB have been investigated. The SNR of 3.2 dB corresponds to the SNR that is experienced by an AS at a distance of 120 nmi from the GS (Ground Station). This is the maximum cell radius intended to be used by the LDACS1 system. As an example, Figure 7 shows the distribution of the number of available LDACS1 channels in Europe for an SNR of 3.7 dB, corresponding to a distance of approx. 113 nmi. In the best case, all 24 channels of the inlay option can be used. As the SNR changes to higher values, the number of available channels per bin increases dramatically. At 5.2 dB, i.e. at a corresponding distance of approx. 95 nmi from the GS, practically all 24 channels can be used everywhere. This is an important result, since TMA zones typically have a 60 nmi radius and therefore are not affected by DME interference, provided that the transmit power of the GS is not reduced. For each rectangular bin of the map in Figure 7, the color indicates the number of available LDACS1 FL channels, i.e. the number of channels for which DME interference does not cause a BER larger than $1\cdot10^{-6}$. For this example SNR of 3.7 dB, all bins have at least nine available channels, and many bins can actually use all 24 channels. For more details on the interference modeling, please refer to [7].

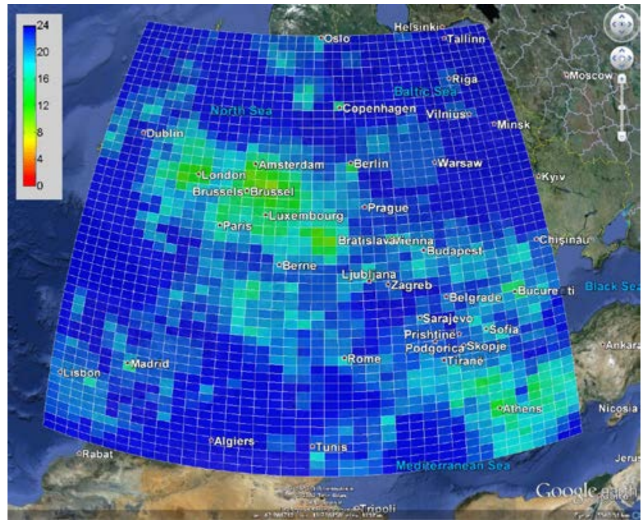

Figure 7. Map of number of available LDACS1 channels for SNR = 3.7 dB

We require a BER below $1\cdot10^{-6}$ in every cell. Typically, an LDACS1 cell will cover many bins of the interference map. For each bin, we calculate the SNR with which the transmission by the GS is received by an AS located at the bin center. Bins that are closer to the cell's center will have a higher SNR than bins that are close to the cell edge, and will therefore also typically have a larger number of channels fulfilling the target BER. This is the set of channels that can be used reliably in that bin. The set of channels that can be used in the entire LDACS1 cell are those channels that can be used successfully in all bins that are covered by this cell.

Frequency Planning Algorithm

For the allocation of LDACS1 channels to the cells provided by the cell planning step, we again define a simple greedy algorithm. The basic idea is to first assign channels to those cells that have the smallest number of suitable channels that can be used in that cell. This list of candidate channels can change with every new allocation, since co-channel interference between LDACS1 cells must also be considered. According to the link budget calculation in [7], an SNR of 3.2 dB at the cell edge is sufficient to achieve the target BER of $1 \cdot 10^{-6}$ in the en-route domain in the presence of interference from other systems. Since the LDACS1 spectrum is relatively flat, its effects on an unintended receiver are similar to the effects of thermal noise. When co-channel interference from multiple cells is present, their signals add up, making the signal even more noise-like [16]. Therefore, we will assume that the co-channel interference is seen as noise and must be considered in each cell's required SNR. For the carrier strength, we assume that an AS is located at the cell edge and calculate the received power according to free space path loss. Obviously, the strength of the co-channel interference depends on the exact location of the aircraft at the cell edge. Therefore, we consider 16 points equally spaced along the circle defining the cell edge. These points are located at FL 450, corresponding to an altitude of approx. 13.7 km, which is well above the typical en-route flight levels. According to [17], FL 450 is the upper limit of en-route cells. Obviously, the signal strength of the serving GS is identical for all of these points.

For each of these points, we calculate the interference that is generated by all other LDACS1 cells that are on the same channel and are within the radio horizon of the point. The co-channel interference from all interfering cells is added up to the cumulative interference, which is then used to calculate the SNR at this point. For all 16 points on the cell edge, the achieved SNR must be above the required SNR of 3.2 dB.

In the following, we will describe the frequency planning algorithm used in our work. The algorithm divides the cells into two sets: a set of cells that have already been assigned a channel, and a set of those that have not. Initially, the set of assigned cells is empty, and the set of unassigned cells includes all cells that result from the previous cell planning step. Each cell is associated with a set of candidate channels, i.e. those channels that fulfill the following conditions: The candidate channels must be in the list of available channels for this cell according to the interference map. The candidate channels must fulfill the SNR requirement for receivers within this cell, where the noise power depends on those cells that have already been assigned this channel. Finally, the candidate channels must, if assigned to this cell, not lead to a violation of the required SNR at another cell that has already been assigned this channel. Initially, no channels have been assigned to any cells, and the candidate channels are given by the results from the interference map alone.

In each step of the algorithm, the unassigned cells are sorted according to their number of candidate channels. The algorithm then selects the cell with the fewest candidates and randomly picks one of these candidate channels. It then attempts to assign this channel to the cell. To do this, it first checks if the allocation of this channel to the current cell would result in a SNR violation in any cell that has already been assigned this channel. The interference levels of all cells within the radio horizon are updated, and their SNR values at the cell edge are calculated. If a violation of the required SNR is detected at any of the already assigned cells, the channel is removed from the current cell's candidate channels, and the algorithm attempts to assign another channel to this cell. If no SNR violation is found for the already active cells, the channel is assigned to the cell, and the cell is moved from the set of unassigned cells to the set of assigned cells.

The algorithm then proceeds to update the interference levels of the inactive cells. If the additional interference caused by this new allocation results in a violation of the required SNR at any of the unassigned cells, this channel is removed from that unassigned cell's set of candidate channels. The algorithm then proceeds to the next iteration, again sorting the cells according to their number of candidate channels and selecting the cell with the fewest candidates.

If any cell's list of candidate channels ever becomes empty before all cells have been assigned a channel, the algorithm has failed to find a solution and terminates. However, due to the random selection of a channel at the beginning of each step, the algorithm may find a feasible solution if it is started again.

Frequency Planning Results

We have addressed the frequency planning problem for both the inlay and the non-inlay deployment scenarios for LDACS1. In the non-inlay case, eleven channels are available, which are all free of DME interference. Therefore, each channel can, in principle, be used in any cell. In the inlay case, 24 channels are available, but not every channel can be used everywhere because of the DME interference. In both cases, co-channel interference between LDACS1 cells must be considered.

As input for the frequency planning step, we use the results of the cell planning algorithm that was described in one of the preceding sections. We run the frequency planning algorithm for both the 120/120 nmi scenario and the 60/120 nmi scenario. Channels must be allocated to 95 cells in the former case and to 106 cells in the latter case. The number of channels that are required by the frequency planning algorithm is shown in Table 1: Although the 60/120 nmi scenario has to assign frequencies to 11 cells more than the 120/120 nmi scenario, it requires only one additional channel. An important result is that the presence of DME interference in the inlay case requires only two additional channels compared to the DME interference free non-inlay case.

The L-band offers 24 inlay and 11 non-inlay channels for LDACS1, yielding a total of 35 channels. The pure non-inlay deployment option requires most of the 11 channels that are available. In contrast, the inlay deployment option only needs about half of the 24 available channels, and could also use the 11 channels of the non-inlay option. Therefore, we conclude that a system equipped with features that enable coexistence with DME equipment offers roughly three times the total capacity than a system without such inlay capabilities. LDACS1 provides many options to accommodate future traffic growth or place additional cells at further airspaces or airports which require additional capacity.

The resulting frequency allocations are shown in Figure 8 for the 120/120 nmi case and in Figure 9 for the 60/120 nmi case, both for the inlay deployment scenario. The different channels are indicated by the different colors and line styles of the range rings.

Table 1. Number of channels required for different deployment scenarios

	inlay	non-inlay
120/120 nmi	11	9
60/120 nmi	12	10

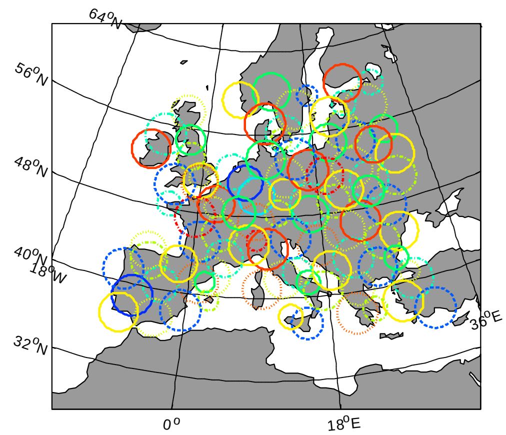

Figure 8. Frequency planning results for 120/120 nmi inlay scenario

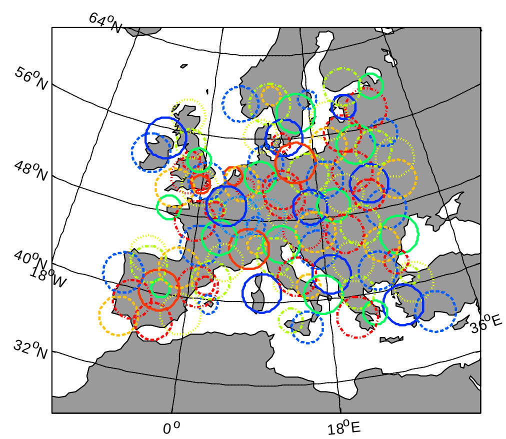

Figure 9. Frequency planning results for 60/120 nmi inlay scenario

The effect of the co-channel interference is shown in Figure 10 for the 60/120 nmi non-inlay scenario. The 106 active cells have a total of 1696 interference test points located along their cell edges. Of these points, 1548 see no co-channel interference at all, because there is no LDACS1 cell on the same channel within the radio horizon. A histogram of the SNR experienced at the remaining 148 points is shown in Figure 10. In general, it can be concluded that the effect of co-channel interference is quite limited in this scenario.

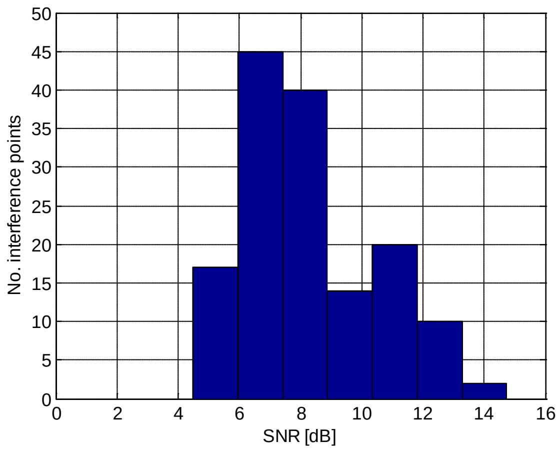

Figure 10. Distribution of SNR values with co-channel interference at interference test points for 60/120 nmi non-inlay scenario

Conclusion

In this paper, we have assessed the feasibility of a Europe-wide deployment of LDACS1. This analysis was based on realistic data traffic, scaled to the year 2020, and detailed models of the DME and co-channel interference. Simple greedy iterative algorithms have been proposed for the cell planning and the frequency planning aspects of the network planning problem. We applied these algorithms to two different cell planning scenarios: A first scenario, in which all cells are limited to a maximum range of 120 nmi, and a second scenario, in which the cells at the largest airports are limited to 60 nmi. The frequency planning step addressed both the inlay and the non-inlay deployment options for the L-band. In all cases, a feasible network planning solution was found. The resulting cell layout is easily able to support twice the traffic expected for 2020, approximately corresponding to the year 2035.

These solutions provide ample room for a further increase in air traffic, since the maximum cell load is 125 kbps in the 120/120 nmi scenario, which is far away from the 300 kbps that the LDACS1 FL can handle even with the most robust coding and modulation scheme. Also, only half of the available channels were required for the inlay option, leaving the other half of the channels free for future growth. Compared to the non-inlay scenario, the inlay scenario only requires two additional channels. This indicates that LDACS1 can coexist well with the DME stations that are already active in the L-band. Network planning approaches that are more sophisticated than our greedy iterative algorithms may be able to provide still more efficient solutions.

Combinations of the inlay and non-inlay approaches would also be possible, giving even more capacity. This capacity may be required if more TMA zones require LDACS1 coverage down to the airport surface, i.e. for departing or arriving aircraft, or if redundant coverage is required in order to increase the network reliability.

In the future, detailed LDACS1 link layer simulations are performed, based on the results of our network planning in order to verify that the quality of service requirements formulated in the COCR are fulfilled. In addition, terrain models could also be incorporated into the network planning process, and frequency planning for the Reverse Link could be considered.

Summarizing, the results of our network planning study are very promising and indicate that LDACS1 can easily cope with the future air traffic communication demand in Europe. Despite our conservative assumption of 300 kbps capacity per cell, only half of the channels available in the inlay deployment scenario are used.

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31st Digital Avionics Systems Conference

October 14-18, 2012