B-AMC – AERONAUTICAL BROADBAND COMMUNICATION IN THE L-BAND

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ABSTRACT

B-AMC (Broadband Aeronautical Multi-Carrier communications) is a proposal for a future aeronautical communications system to be operated in the aeronautical L-band. B-AMC is based on the results of the Broadband-VHF (B-VHF) project, although, due to the different spectrum allocation and propagation conditions in the L-band, basic physical layer parameters had to be adapted. In that process, the physical layer has been redesigned such as to support air to ground (A/G) communication as well as direct air to air (A/A) communication without requiring a ground relay station. The B-AMC system has been designed to coexist with Distance Measuring Equipment (DME) in terms of interference and duty-cycle. As a result of the physical layer adaptations a different approach for the higher layers has been required. The revised B-AMC data link layer is based on the experience gained during the B-VHF project. One key issue for the revision was the conceptional shift from primarily supporting digital voice to optimised data communications. The other design goals were the definition of a data link protocol stack capable of fulfilling the stringent requirements of the aeronautical environment – providing high performance, low latency and low duty cycle. The B-AMC study is funded by EUROCONTROL.

1. INTRODUCTION

Broadband-VHF (B-VHF) [1] [2] [3] [7] [10] has been a research project co-funded by the European Commission within the Sixth Framework Programme. The project has investigated and demonstrated the feasibility of a new multi-carrier based wideband communication system to support aeronautical communications while operating as an overlay system in the VHF COM band. B-VHF has demonstrated good potential for satisfying the needs of future aeronautical communications, and following an initial investigation of promising technologies, it has emerged on the EUROCONTROL/FAA Future Communications Study (FCS) shortlist as one of the promising candidate technologies. However, the overlay implementation option in the VHF COM band has been considered elaborative and costly and it was the common point of view of EUROCONTROL/FAA that a new data link system for the year 2020 and beyond should preferably be implemented in L-band. For that reason, EUROCONTROL has initiated the investigation of the use of a BVHF-like system in the aeronautical L-band (960-1164 MHz). B-AMC stands for the *Broadband Aeronautical Multi-carrier Communications* system that is currently being developed and is based on the B-VHF system concepts.

The objective of the B-AMC project is to re-use the B-VHF system design in the development of the L-band B-AMC system to the maximum possible extent. The flexibility of the original B-VHF system design has allowed for systematic adjustments to the L-band use, in particular with respect to the data link efficiency and robustness under interference caused by "close" L-band systems. Currently the L-band is mainly used by navigation systems such as DME, UAT, SSR/Mode S and the military Joint Tactical Information Distribution System (JTIDS). B-AMC offers a large co-existence potential with these other systems operating in- and around the aeronautical L-band. In particular, B-VHF side-lobe suppression concepts are re-used within the B-AMC system design for shaping the transmitter signal-in-space, minimising interference to other systems. The duty-cycle of an airborne B-AMC transmitter has been adapted to ease the coexistence with DME. Conversely the B-AMC receiver has been designed to be robust against interference from the existing systems.

Due to the different spectrum allocation and propagation conditions in the L-band basic physical layer parameters have had to be adapted. In that process, the physical layer has been redesigned such as to support A/G communication as well as direct A/A communication without requiring a ground relay station. For A/G communications, B-AMC inherits the functional scope of the B-VHF system and remains based on B-VHF physical layer and protocol concepts. In A/G mode the B-AMC Ground Station (GS) and the associated ground infrastructure are mandatory. For A/A communications, the B-AMC system extends B-VHF capabilities by implementing a dedicated A/A communications mode that can operate without any supporting ground infrastructure.

As a result of the physical layer adaptations a different approach for the higher layers has been required. A key design issue for the data link layer has been the conceptional shift from primarily supporting digital voice to optimised data communications. The revised structure of the B-AMC data link layer is based on the experience gained during the B-VHF project laying the main focus on the definition of a high performance, low latency and low duty-cycle data link protocol stack. For A/G communications a deterministic resource reservation procedure suitable for safety-related data has been devised. Direct A/A communication is a new feature of the B-AMC protocol stack. This mode of communication has been developed based on the concepts of self-organizing mobile ad-hoc networks. With respect to the required voice and data services, the B-AMC system design, as presented in this document, focuses on the two lowest layers of the ISO-OSI model, namely the physical layer (PHY) and the data link layer (DLL).

The first part of this document provides an overview of the A/G B-AMC system architecture. The second part presents selected evaluation results, gained by simulations. The A/A mode is discussed only briefly.

2. SYSTEM ARCHITECTURE

An airborne B-AMC system offers two exclusive modes of operation, one for A/G communications and another one for A/A communications. These two modes use different radio channels with different physical layer and DLL approaches.

The B-AMC A/G sub-system is a cellular broadband system capable of providing various kinds of Air Traffic Service (ATS) and Aeronautical Operational Control (AOC) voice and data link services. The B-AMC GS is the centralised instance that controls B-AMC A/G communications. It is required only in the A/G mode. Within a B-AMC cell all registered A/C are connected to the controlling GS in a star-topology. In this way the B-AMC system supports air-ground data communications. Party-line voice is realized by re-transmissions via the GS. The B-AMC A/G system design includes propagation guard times sufficient for the operation of cell sizes of up to 200 nm radius. However, the physical cell coverage of a multi-service B-AMC system is effectively de-coupled from the operational coverage required for a particular service. Handover between adjacent B-AMC cells is seamless, automatic and fully transparent to the airborne user. Thus, the B-AMC A/G communications concept is open to the future dynamic airspace management concept.

In the B-VHF project, Time-Division Duplex (TDD) was selected to discriminate between forward and reverse link. For the B-AMC A/G sub-system, Frequency-Division Duplex (FDD) has been selected instead of TDD as it is better aligned with the L-band specific interference picture and can provide increased capacity. One full-size broadband channel is continuously used for Forward Link (ground to air), another one for Reverse Link (air to ground). On the RL a combination of TDMA (Time-Division Multiple-Access) and OFDMA (Orthogonal Frequency-Division Multiple-Access) is used. The B-AMC GS transmits continuously on FL using OFDM (Orthogonal Frequency-Division Multiplexing).

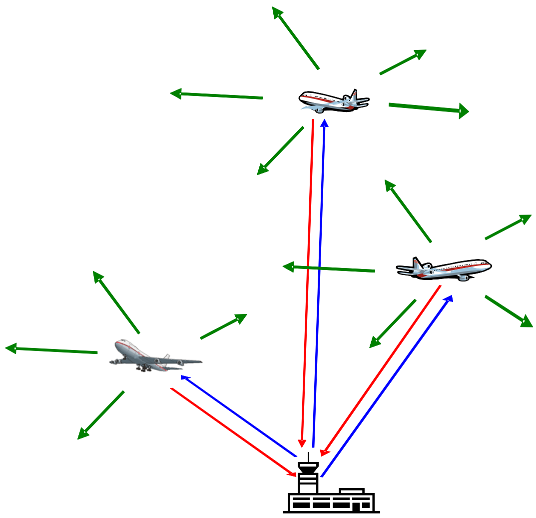

FIG 1. B-AMC topology: The A/G mode uses the RL (red) and FL (blue) and the A/A mode uses a dedicated channel (green).

The B-AMC A/G data link sub-system is designed to be integrated as an ATN/OSI or ATN/IPS sub-network.

A/A communication between aircraft takes place in a decentralized, self-organized way within “communication bubbles” defined by the radio range of the B-AMC terminals and operates in a dedicated global “Common Control Channel” (CCC). The A/A mode offers no voice services.

3. PHYSICAL LAYER

The B-AMC system offers two modes of operation, one for A/G communications and another one for A/A communications. The reason for having two separate modes lies in the fact that the operational concepts and requirements for A/G and A/A communications are completely different which would lead to a spectrally very inefficient implementation if A/G and A/A communications are implemented in an integrated way.

Both modes can be integrated into one airborne B-AMC radio and can operate simultaneously. Since A/G and A/A mode use different frequency sub-bands within the L-band, the B-AMC radio provides two RF branches – one for the A/G and one for the A/A mode.

In the following subsections, the detailed physical layer specifications for B-AMC are given. The B-AMC physical layer design is based on B-VHF [1]. However, there are some physical layer adjustments required which are due to the special L-band conditions as described below.

3.1. Identification of Required Adjustments

3.1.1. Special L-band Conditions

Comparing the L-band to the VHF-band, several differences which are relevant to the physical layer design have to be considered. The interference situation in these two bands is completely different. Within the VHF-band the B-VHF system has been designed as a real overlay system with narrowband interferers contained within the receiving bandwidth, in contrast B-AMC is designed as an “inlay” system, i.e. B-AMC RF channels are intended to be inserted and operated between adjacent DME channels which are considered the main interference source in L-band. Thus, the centre frequencies of interferers are not located within the receiving bandwidth of the B-AMC receiver, but outside, at a relatively close distance. Nevertheless, due to the broad DME spectra, the interference towards B-AMC can not be entirely avoided. Note that the characteristic of the DME interference is different than the interference in the VHF- band since it is more noise-like and bursty instead of narrowband and continuous.

Considering L-band use, the carrier frequency is approximately 7-8 times higher than in VHF-band. This has an effect on the free space propagation loss and on Doppler shifts due to moving airborne transmitter and/or receiver.

3.1.2. Required Adjustments

3.1.2.1. Duplex Scheme for A/G Mode

Instead of using TDD as in B-VHF, FDD is proposed for B-AMC. There are three important reasons for this decision. First, using FDD instead of TDD avoids large guard times that would be required with TDD due to propagation delays. Second, the expected available B-AMC channel bandwidth between successive DME channels is relatively small which leads to a restricted transmission capacity of the B-AMC cell. Further division of this B-AMC cell capacity into Forward Link (FL) and Reverse Link (RL) resulting from TDD should be avoided in order to provide a reasonable amount of capacity. FDD offers the possibility to put FL and RL on two different B-AMC channels and with that the B-AMC capacity is doubled compared to the TDD solution. Third, by properly choosing frequencies for FL and for RL from the right part of the L-band the co-location interference situation at the aircraft can be significantly relieved.

3.1.2.2. Forward Link Access Scheme

Instead of using MC-CDMA (Multi-Carrier Code-Division Multiple-Access) for the FL access-scheme, OFDMA or pure OFDM is proposed for B-AMC FL. Note, pure OFDM is a special case of OFDMA where a single user transmits over all available OFDM sub-carriers. Using pure OFDM in the FL enables packet-switched communication which is preferable when data communication is the primary concern. Moreover, OFDMA (OFDM) is much simpler and achieves performance comparable to MC-CDMA, taking the L-band propagation and interference conditions into account.

3.1.2.3. OFDM Parameters

Within L-band both the propagation conditions and the interference situation is different from the VHF-band. Hence, the OFDM parameters chosen for the B-VHF system had to be adjusted for B-AMC. The most important changes affect the RF bandwidth and the sub-carrier spacing, influencing other OFDM parameters as well. A detailed physical layer description including all relevant OFDM parameters is given in Section 3.2

3.1.2.4. Framing Structure

Changes of the duplex scheme and OFDM parameters, requires a re-design of the framing structure for B-AMC. The detailed B-AMC framing structure is described in Section 4.1.

3.2. Adapted OFDM Parameters for A/G Mode

Currently, a bandwidth of around 500 kHz is considered to be available for each B-AMC channel (FL or RL). Based on this finding, the set of OFDM parameters is derived in the following.

The most important physical layer parameter is the sub-carrier spacing Δf, since after choosing this parameter most other parameters can be deduced in a straight forward way. The choice of the sub-carrier spacing is mainly influenced by the propagation conditions, i.e. by the coherence bandwidth of the transmission channel and the expected Doppler spread. For B-AMC the same transmission scenarios as for B-VHF are considered, namely parking, taxiing, take-off/landing, and en-route scenario [1]. Based on the same aircraft speeds defined for these scenarios, the maximum Doppler shift can be calculated, which gives 19, 192, 537, and 997 Hz for the four scenarios, respectively. Taking into account that the en-route scenario is almost a line-of-sight communication, the relative movement between transmitter and receiver just translates into a Doppler shift without significant Doppler spread. Therefore, the Doppler frequency for the take-off/landing scenario is the worst case to be considered for the choice of the sub-carrier spacing. To be able to neglect Inter-Carrier Interference (ICI) the sub-carrier spacing should be at least 10 times larger than the worst case Doppler spread which implies that $\Delta f > 5.4$ kHz.

Moreover, the sub-carrier spacing has to be smaller than the coherence bandwidth of the channel. The considered transmission channel all have a coherence bandwidth well above 50 kHz which leads to the conclusion that the sub-carrier spacing shall be chosen within 5.4 kHz < Δf < 50 kHz.

Taking into account that the out-of band radiation of an OFDM transmission signal decays faster the smaller the sub-carrier spacing is, a large number of sub-carriers with lower spacing is preferable to avoid interference towards legacy L-band systems, like DME. Thus, the length of the Fast Fourier Transform (FFT), which is identical to the maximum number of sub-carriers that can be used by the system, is chosen to be N_c = 64 with $N_{c,used}$ = 48 sub-carriers effectively used for data transmission. Of the remaining 16 sub-carriers 12 (6 at each side) are used as empty guard sub-carriers, while four (2 at each side) are used as cancellation carriers, i.e. N_{cancel} = 4. The guard bands left and right can be used for filtering purposes and the cancellation carriers are used as in B-VHF [1] for sidelobe suppression to reduce the out-of-band radiation of B-AMC towards other legacy L-band systems, especially DME.

With the available bandwidth of B = 500 kHz and $N_{c,used}$ = 48 used sub-carriers the sub-carrier spacing results in

$$\Delta f = \frac{500 \text{ kHz}}{48} = 10.41\overline{6} \text{ kHz} \cdot$$

The OFDM symbol duration T_o directly follows from the sub-carrier spacing Δf

$$T_o = \frac{1}{\Delta f} = 96 \ \mu\text{s} \cdot$$

In order to avoid Inter-Symbol Interference (ISI) a guard interval in the form of a cyclic prefix is introduced. The guard interval duration T_g is chosen to be

$$T_g = 24 \ \mu\text{s}$$

resulting in an overall OFDM symbol duration T_{og} including the guard interval of

$$T_{og} = T_o + T_g = 120 \ \mu\text{s} \cdot$$

With 20% of the overall OFDM symbol duration the guard interval is relatively long. The reason for this choice is that the guard interval fulfils two tasks. One half of the guard interval is used as "classical" guard time to avoid ISI of successive OFDM symbols. The other half is used to enable transmit windowing based on a raised-cosine window with roll-off factor α = 0.1. Note, transmit windowing further decreases out-of-band radiation as it has already been proven within B-VHF.

N_s = 54 OFDM symbols are grouped into an OFDM frame. With that the duration T_f of an OFDM frame is

$$T_f = N_s \cdot T_{og} = 6.48 \text{ ms} \cdot$$

For synchronization two symbols at the beginning of each OFDM frame are used. Strictly speaking, the second synchronization symbol is a combined synchronization and pilot symbol which is also used for channel estimation. Other pilot symbols for channel estimation are chosen with pilot symbol distances according to the worst expected channel alteration in time and frequency direction. Taking into account propagation conditions the pilot symbol spacing in time N_t and frequency N_f direction has to be

$$N_f \leq 2, \ N_t \leq 13$$

according to the sampling theorem with two times oversampling. The proposed choices for the pilot spacing are N_f = 1 and N_t = 12. The resulting standard B-AMC OFDM frame for FL is shown in FIG 2.

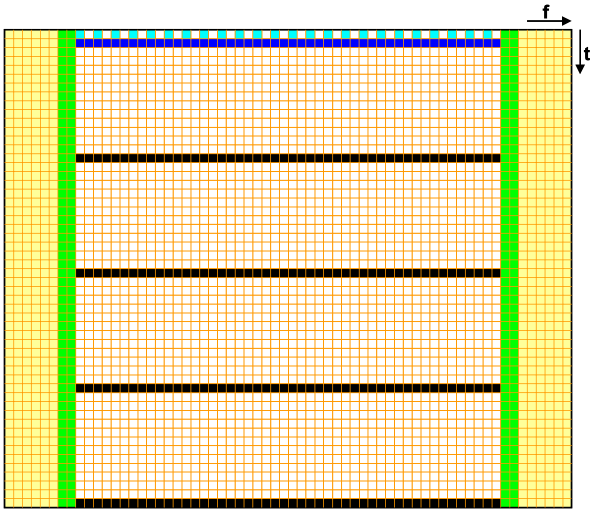

FIG 2. Standard B-AMC OFDM frame (FL).

3.3. Structure of Physical Layer OFDM Frames

The smallest unit for both FL and RL is the OFDM frame which serves as a transmission container for different kinds of information. As payload, OFDM frames contain either signalling information (OFDM signalling frames) or user data (OFDM data frames). Although FL and RL differ slightly, since for RL transmission no synchronization symbols are required, both OFDM frames consist of N_s = 54 OFDM symbols and, therefore, have the same frame duration which is equal to T_f = 6.48 ms. In FL and the RL, 48 and 50 OFDM symbols are available for transmission of useful data in an OFDM data frame, respectively.

OFDM signalling frames are special frames that do not carry user information. The following types of dedicated OFDM signalling frames exist:

- Broadcast (BC) frame – control information is broadcasted to all users (FL)
- Random Access (RA) frame – all users send their net entry requests (RL)

BC and RA signalling frames have a specific internal structure. A BC frame consists of N_s = 56 OFDM symbols and therefore, has a frame duration equal to T_{BC} = 6.72 ms. The BC frame consists of three sub-frames and is used in FL only to pronounce common GS information to the aircraft within the B-AMC cell. Additionally, the BC frame of a GS enables aircraft in neighbouring B-AMC cells to synchronize and listen to this GS in order to prepare for a B-AMC cell handover.

The RA frame is used in RL and enables net entry to newly arriving aircraft. Two short RA frames appear within the RA slot. The duration of the RA slot is the same as that for the BC frame, i.e. T_{RA} = T_{BC} = 6.72 ms. The RA slot appears in the RL at the same time as the BC frame is transmitted in the FL.

4. A/G DATA LINK LAYER

The high-level design of the B-AMC data link layer is analogue to the B-VHF design [5] [6], although some adjustments had to be made due to the shift from the VHF-band into the L-band. Most of these adjustments concern the medium access sub-layer (MAC) and are related to the usage of FDD instead of TDD. The B-AMC protocol layer structure puts a strong emphasis on clear layering to allow its components to work in both modes (A/A and A/G) over the respective MAC sub-layers with minimal modifications. The B-AMC data link comprises two sub-layers and six major entities.

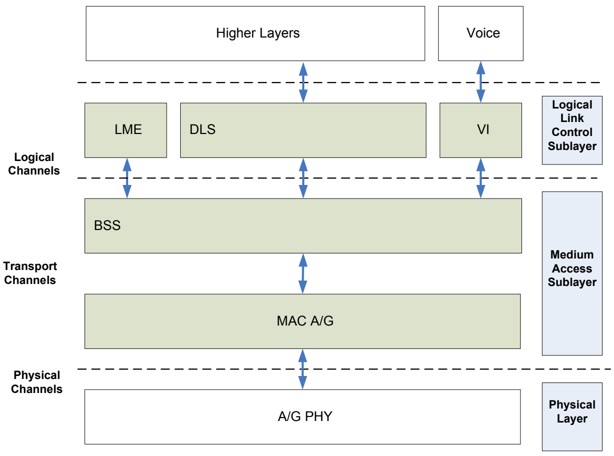

FIG 3. B-AMC protocol stack in A/G mode.

The Medium Access sub-layer comprises the B-AMC Special Services (BSS) entity and the Medium Access (MAC) entities. The BSS entity maps logical channels to transport channels. Below the BSS resides the MAC entity, which has the task to map transport channels to appropriate physical channels. Conceptually, the BSS and MAC entities constitute the medium access sub-layer.

The Logical Link Control (LLC) sub-layer manages the radio link and offers to the higher layers connection-less transport services with different levels of Quality of Service (QoS). It is up to the LLC layer to achieve the required level of data integrity, using Automatic Repeat Request (ARQ) and checksums, and to support priorities between QoS classes by mapping higher layer packets to appropriate logical channels. The LLC contains the Link Management Entity (LME), the Data Link Services (DLS), and the Voice Interface (VI).

4.1. B-AMC Frame Structure

The B-AMC medium access sub-layer uses the framed structure provided by the physical layer to create a slotted time structure. B-AMC FL and RL OFDM frames are grouped together to build a Multi-Frame (MF) with a duration of

$$T_{MF} = 58.32 \text{ ms}.$$

Both FL and RL MF comprise 9 time slots (9 * 6.48 = 58.32 ms) each containing one data OFDM frame.

On the FL the first slot (Common Control (CC) slot) of each multi-frame is used for a $TN_{c,used}$ (see 4.2) transport channel carrying the logical Common Control Channel (CCCH). The main purpose of the CCCH is to assign RL transport channels to different A/C. The remaining 8 slots of the FL multi-frame are used for the transmission of the $TN_{c,used}$ transport channel containing the logical channels of the traffic plane (voice, data and management information).

On the RL there are only 7 data slots and two special slots. The Synchronized Access (SA) slot is used for the logical Synchronized Access Channel (SACH). Within this slot only "low-bandwidth" *T1* (see 4.2) transport channels are used. At net entry, each A/C is assigned one *T1* transport channel (i.e. one OFDMA sub-carrier; see section 4.2), thus the system provides to each of up to $N_{c,used}$ A/C with a dedicated low bit-rate transport channel for its SACH. If the number of A/C exceeds $N_{c,used}$, the SACH assignments are distributed over the SA slots of several MFs. The Dedicated Control (DC) slot has the same structure as the SA slot and uses the same assignment policy. It is used to provide each A/C with a dedicated low bit-rate transport channel for its logical Dedicated Control Channel (DCCH), which conveys LLC signalling information.

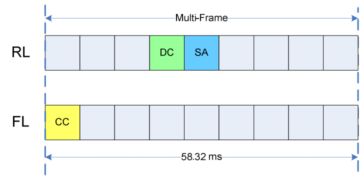

FIG 4. B-AMC slot structure – Multi Frame (MF).

The positions of the "special" slots (CC, SA, and DC) within the multi-frame have been chosen to give the radio equipment enough processing time (2-4 slot lengths ~ 12 – 25 ms). In front of four RL MFs one Random Access (RA) / Broadcast (BC) slot is inserted, containing a RA-frame that carries a *TRA* transport channel/logical Random Access Channel (RACH). Similarly, the BC-frame which conveys a *TBC* transport channel/logical Broadcast Channel (BCCH) is inserted on the FL (BC and RA slots coincide in time). These channels are used during net-entry and hand-over. One RA/BC slot and four MFs comprise one super-frame. The super frame has an overall length of

$$T_{SF} = 240 \text{ ms}.$$

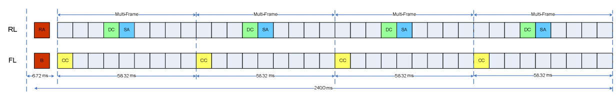

FIG 5. B-AMC Super Frame (SF) structure.

4.2. B-AMC Channel Structure

Each of B-AMC data link layer protocol sub-layers provides services to the sub-layer above. The services are offered in the form of communications channels. Three types of channels exist:

Logical channels - The BSS-entity of the medium access sub-layer provides data transfer services to higher DLL entities of the LLC sub-layer (LME, DLS, Voice Interface) on logical channels. Each logical channel type is defined by what type of information is transferred. B-AMC logical channels can be classified into control channels (Broadcast Control Channel (BCCH), Random Access Channel (RACH), Synchronized Access Channel (SACH), Dedicated Control Channel (DCCH), and Common Control Channel (CCCH)) for the transfer of control plane information) and traffic channels (Data Channel (DCH), Voice Channel (VCH)) for the transfer of user plane information.

Transport channels - The MAC-entity provides data transfer services to BSS-entity on transport channels. Each transport channel type is defined by how the information is transferred. A set of transport channel types (*TBC, TRA, T1, T2… $TN_{c,used}$*) is defined for different kinds of data transfer services. Different types of transport channels (different transmission bandwidths) are realized by assigning an appropriate number *n* of distinct OFDM sub-carriers to each transport channel type *Tn* (for *n* in 1… 48). The actual mapping of transport channels to physical channels (i.e. sub-carriers of OFDMA frames) is performed by the physical layer.

Traffic Channel Type	T48	T24	T12	T6	T3
QPSK Data Symbols	2304	1152	576	288	144
Coding Rate	0,44	0,44	0,44	0,43	0,41
Traffic Channel Capacity/slot (bits)	2027	1013	506	247	118
Available User Data Rate FL (kbit/s)	270,27				
Available User Data Rate RL (kbit/s)	236,48				

TAB 1. Exemplary transport channel definition for $N_{c,used}$ = 48 and n = 48, 24, 12, 6, 3.

While the mapping of logical control channels to corresponding transport channels is fixed, the logical traffic channels (DCH, VCH) may be mapped onto several types of transport channels, dependent on the required bandwidth. Within each slot (i.e. OFDM-frame) an integral number of transport channels may be allocated in parallel. These transport channels are mapped to time slots by the MAC. Transport channels are assigned by the GS, per slot, using the resource acquisition mechanism (section 4.3.3).

Physical channels - Physical channels consist of selections (groups) of OFDMA sub-carriers in the slotted TDMA frame structure defined by MAC. While some slots (i.e. OFDM frames) (RA and BC OFDM frames) carry dedicated signalling information, others (DATA OFDM frames) may – as dictated by the MAC-entity - carry either signalling information or user data. Physical channels are mapped to OFDM-frames by the physical layer.

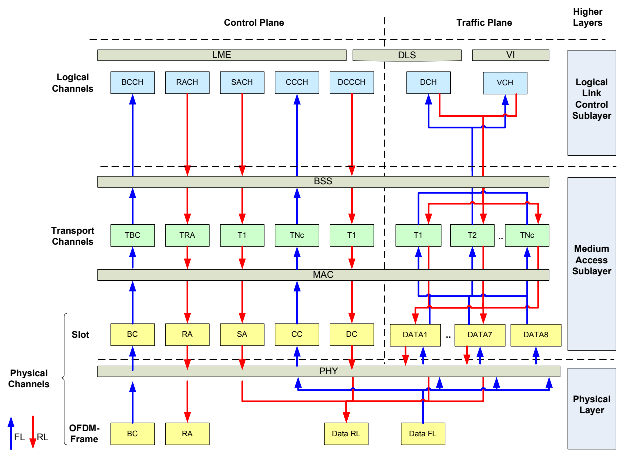

FIG 6. B-AMC channel mapping.

4.3. Medium Access Sub-Layer

The A/G Medium Access sub-layer comprises the B-AMC Special Services (BSS) entity and the Medium Access (MAC) entity. Conceptually, the BSS and MAC entities constitute the medium access sub-layer.

4.3.1. BSS

The BSS entity maps logical channels to transport channels. It provides a sending and a receiving buffer for each transport channel and injects or extracts data link frames (DLL-PDUs) from the transport channels. Each DLL-PDU received from the LLC sub-layer is put into the BSS queue corresponding to the transport channel. Whenever the BSS is granted a transport channel by the MAC entity (using the resource acquisition mechanism (section 4.3.3)) the contents (or a part of the contents) of the transport channel queue is injected into the granted transport channel.

4.3.2. MAC

The MAC entity maps transport channels to physical channels of the A/G radio link. The general approach of B-AMC A/G MAC solution is that the FL and RL (which are separated by FDD) are themselves structured in time slots. These slots are managed by the algorithms of the MAC sub-layer. Each slot contains one OFDM frame carrying information of one or more transport channels. On the RL, different A/C may transmit simultaneously on different transport channels within the same data-frame, towards the GS being separated by OFDMA. Transport channel capacity is requested by the A/C MAC entity and is allocated by the GS. The resource request algorithm is contention-free and realized through the dedicated Synchronized Access Channel (SACH).

4.3.3. Resource Allocation

On the FL the GS directly allocates FL resources and manages access priorities. On the RL, the GS MAC resource allocation function manages the assignment of RL slots and transport channels to different A/C in a scheduled, contention-free manner. In order to be included in the assignment, each A/C has to report its resource needs on

RL to the ground-station in advance via the SACH logical channel. On the basis of these reports, the GS will allocate RL resources by using the FL CCCH logical channel. The resource requesting assignment cycle is shown in FIG 7, assuming less than $N_{c,used}$ airborne users. For more than $N_{c,used}$ users, the cycle extends over an appropriate number of MFs.

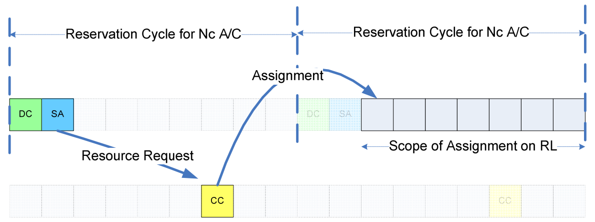

FIG 7. Reservation cycle for $N_{c,used}$ A/C.

The average length of the reservation cycle grows linearly with the number of users and provides each A/C with one dedicated resource request opportunity in every cycle. Under the assumption that the GS can grant the reservation request, the algorithm has a deterministic upper bound for the medium access delay, guaranteeing medium access in linear time:

$$E(\text{medium access on } RL) = 2\frac{users}{N_{c,used}} 60.0\,ms \tag{1}$$

$$\text{medium access on } RL \le 2\left\lceil \frac{\text{users}}{N_{c,used}} \right\rceil 60.0\,ms \tag{2}$$

If the GS can not grant the reservation request immediately the access times increase by the queuing delay.

4.4. Logical Link Control Sub-Layer

The upper sub-layer of the B-AMC data link layer is the logical Link Control (LLC) sub-layer. The LLC manages the radio link and offers connection-less transport services with different levels of Quality of Service (QoS) to the higher layers.

The B-AMC Data Link Services entity (DLS) of the LLC provides connectionless communication supporting different traffic classes (CoS) each having different QoS expectations. Where the required integrity of a traffic class cannot be achieved by using only FEC in the physical layer, the DLS improves integrity using an ARQ protocol and a second level of “outer” coding (Reed Solomon). The DLS uses the logical data channel DCH for the transmission of user data and the DCCH channel for signalling (e.g. ARQ acknowledgements).

The B-AMC Link Management Entity (LME) functionality comprises the B-AMC system procedures (net-entry, net-exit, handover). It uses the BCCH and RACH logical channels during net-entry and the CCCH, SACH and DCCH during normal operations for signalling.

5. SIMULATION RESULTS

5.1. Physical layer

The performance of the PHY layer designed for B-AMC is accessed by simulations using the PHY layer parameters described in Chapter 2. In addition, propagation conditions and interference being characteristic for the L-band are considered.

The impact of interference from DME systems operating in channels close to the centre frequency of the B-AMC system is simulated by generating the DME Tx signal, i.e. a Gaussian-shaped pulse pair in time domain. If multiple DME stations are present their interference contributions are summed up. The resulting interference signal received by the B-AMC victim receiver is processed in the same way as the desired B-AMC signal would be processed taking into account RF filtering, an anti-aliasing filter and the B-AMC sampling rate. Finally, the interference signal is transformed to frequency domain by a 64-point FFT as used in B-AMC. That way, the contribution of interference to each OFDM sub-carrier is obtained.

In FIG 8, the spectrum of an interference signal with four DME interferers at +/-1.5 and +/- 0.5 MHz offset from the B-AMC centre frequency is shown, respectively. The power density of the interference signal within the B-AMC bandwidth from -250 kHz to +250 kHz is significantly above the receiver noise power density in the right half of the bandwidth due to the relatively high power of the interferer in the channel at 0.5 MHz offset. The strong impact of interference has to be mitigated e.g. by means of powerful coding. In FIG 8, the DME duty-cycle is assumed to be 100%. With realistic interference scenarios, 2700 or 3600 pulse pairs per second (ppps) are generated for a DME or a Tactical Air Navigation (TACAN) station, respectively. Taking into account the duration of an OFMD symbol, up to every third OFDM symbol may be affected by interference. If more than one DME station per channel contributes to the interference and/or if interferers occur in both channels at +0.5 and -0.5 MHz offset from the B-AMC centre frequency, the overall duty-cycle increases such that nearly every OFDM symbol within one OFDM frame is affected.

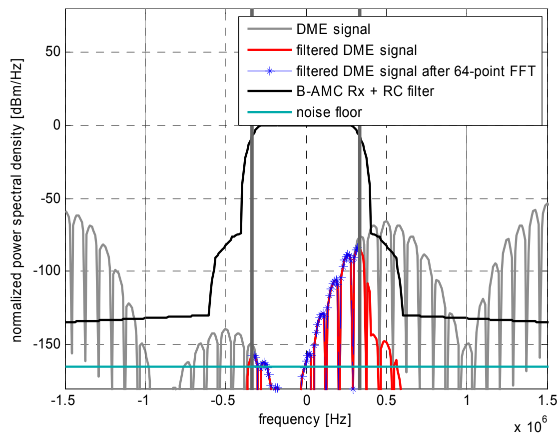

FIG 8. Spectrum of interference signal with four DME interferers.

The actual number of interferers, their power, duty-cycle, and the distance between the two pulses of a pulse pair, are derived from NAVSIM data [9]. With the NAVSIM tool, the allocation of L-band channels for an arbitrary area within Europe can be derived from a real database of DME channel allocations. Moreover, a victim receiver can be positioned at an arbitrary flight level within that area. The interference power from each DME or TACAN station received by the victim receiver is determined taking into account the Tx EIRP of each DME/TACAN station, free space loss as well as antenna patterns of the transmitting DME/TACAN stations and the receiving aircraft.

The NAVSIM tool has identified Paris, Charles-de-Gaulle, as that area in Europe with the highest density of DME and TACAN ground stations. When the B-AMC system shall be operated in that area, the B-AMC centre frequency is chosen such as to minimize interference from DME/TACAN stations. In the band 985-1009 MHz planned for the B-AMC forward link, 995.5 MHz is identified as the most appropriate centre frequency for B-AMC based on a criterion for minimizing the total interference power in the four adjacent channels. Note, a pre-requisite for this selection is that frequency planning will be applied for determining the B-AMC centre frequencies.

Station	Frequency [MHz]	Interference power at victim Rx	Duty cycle
TACAN	994	-86.4 dBm	3600
TACAN	994	-84.8 dBm	3600
-	995	-	-
B-AMC	995.5		
DME	996	-86.4 dBm	2700
DME	997	-84.0 dBm	2700
DME	997	-88.9 dBm	2700
DME	997	-88.1 dBm	2700
DME	997	-84.8 dBm	2700

TAB 2. Interference scenario with frequency planning for forward link, en-route FL450.

The interfering DME/TACAN stations derived from the NAVSIM tool are listed in TAB 2 for an en-route scenario at FL450. The spectrum of the interference signal with 100% duty-cycle of all interferers is shown in FIG 8. This scenario represents a typical interference situation that can be achieved with frequency planning. However, this scenario is also based on worst-case conditions, as the worst case with respect to the duty-cycle is considered. Moreover, the densest area in Europe is regarded and the B-AMC centre frequency is selected according to a very simple criterion which can be further improved.

The performance of the PHY layer in presence of the interference defined above is evaluated by simulations of the FL transmission in an en-route cell. The parameters are chosen according to the PHY layer design presented in Chapter 2, e.g. 54 OFDM symbols per frame, 48 used sub-carriers, and a 64-point FFT. Since perfect channel estimation and synchronization are assumed, all 54 OFDM symbols within one frame are used for data transmission. The data symbols are QPSK modulated and an inner (133,171)-convolutional code with rate ½ in combination with an outer (161,144) Reed-Solomon (RS) code from Galois field $GF(2^4)$ with rate 0.89 is applied. The en-route channel is modelled by an appropriate channel model adapted to the L-band taking into account Doppler effects, a strong line-of-sight (LOS) component, and one delayed path. In the simulations, the noise level N_0 is kept fix at -165 dBm/Hz taking into account thermal noise with density -174 dBm/Hz and the receiver noise figure of 9 dB. The power of the interferers is chosen according to the NAVSIM data given in TAB 2 and is constant for all simulations. The level of the received power is varied in order to be able to determine the power required to receive and decode the desired B-AMC signal with a certain quality.

In FIG 9, the frame error rate (FER) vs. Eb/N0 is shown. Compared to the case without interference, the performance is decreased by 23 dB at a FER of 10^{-2} when interference is present and only the inner convolutional code is applied. The outer RS code is capable to correct several errors induced by interference and the performance is improved by about 10 dB. As expected from FIG 8, the interferer at 0.5 MHz offset from the B-AMC centre frequency has the most significant impact. When this interferer is omitted, the performance of the interference-free case is nearly achieved.

However, in reality, interferers in channels at only 0.5 MHz offset can not be avoided. Nevertheless, a good performance is achieved for Eb/N0=20 dB when all interferers – including the most significant one - are taken into account with maximum duty-cycle. Due to the RS code, a BER and FER of only 2.5e-5 and 8.8e-4 are achieved, respectively. Eb/N0=20 dB translates into an Rx sensitivity of -90 dBm which is an acceptable value. Hence, it can be concluded that the designed B-AMC system with an assumed bandwidth of 500 kHz works properly in the described scenario even in presence of interference from DME/TACAN stations in channels at only small offsets to the B-AMC centre frequency. A pre-requisite is that the B-AMC centre frequency is selected such as to keep interference from other L-band systems at a minimum.

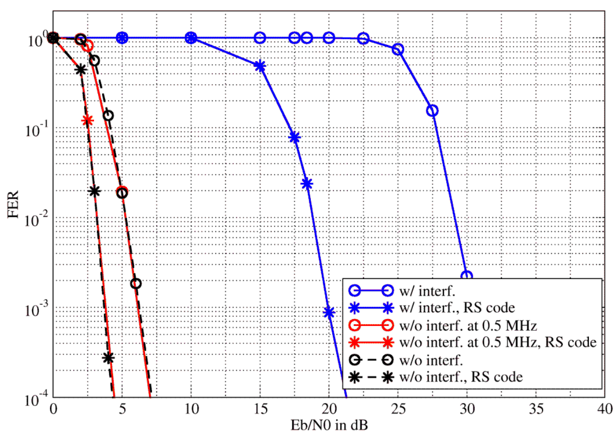

FIG 9. FER vs. Eb/N0 for the constant interference scenario at FL450 defined in TAB 2.

5.2. Data Link Layer

The data link layer performance evaluation has been carried out on top of the physical layer simulations using the BER/FER as parameter. The simulation scenarios have been taken from [9] and are based on COCR phase 2 [4] (see TAB 3).

Scenario	PIAC	FL (kbps)	RL (kbps)
ENR Small	45	80	30
ENR Medium	62	100	30
ENR Large	204	200	40

TAB 3. FCI en-route simulation scenarios taken from [9] (additionally 10% overhead were considered).

In this document the results for the en-route scenarios (small, medium and large) are presented. A/C have been assumed to arrive at the cell boundaries at the rate of 0.5 A/C per second. The data traffic volumes (ATS and AOC combined without Auto Exec) have been increased by further 10% to include any possible overhead of B-AMC. According to most frequent message size specified in [4] the packet sizes have been chosen to be approximately 1000 Bit. Consequently it has been assumed that A/C are always assigned *T24* (=1027 Bit) traffic channels on the RL. No priority management has been considered yet.

TAB 4 displays the simulation results of the mean and 95%-quantile of the one-way latency. The results are compared with the Required Communication Technical Performance (RCTP). All simulations have been carried out multiple times using different random seeds.

	Avg. Latency - 1 way (s)		Latency TT_{95} – 1 way (s)	
	FL	RL	FL	RL
RCTP	-		1.4	
ENR Small	0.011	0.124	0.019	0.153
ENR Medium	0.012	0.300	0.020	0.408
ENR Large	0.024	0.562	0.055	0.858

TAB 4. Simulation results and requirements for one-way latency, scenario En-Route.

The results of performance evaluations show a good correlation to the mathematical model. Furthermore latency figures presented comply with the required numbers. To understand the chart presented in FIG 10 it has to be pointed out that an A/C gets at most one complete OFDMA frame per reservation cycle. A reservation request is granted not earlier than in the next reservation cycle. This has been defined to increase fairness among different users. This measure has side effects. The positive part is that with larger DLS data packets the amount of transmissions is reduced, hence the B-AMC TX duty cycle is lower, which is advantageous in terms of co-existence with DME. The negative part is that larger DLS data packets are rather exposed to bit errors than smaller ones, which will cause more frequent re-transmissions. Additionally timers which are triggered at DLS level increase re-transmissions, too. This has a more negative effect in this special case with larger data packets than with smaller ones. Consequently the BSS transmit queues get larger, which will cause delays at the medium access. In this case the theoretical values of equations (1) and (2) are increased by an additional queuing delay of 1 or 2 reservation cycles. FIG 10 shows the histogram of the one way delay of the RL. Within the diagram the described negative effect manifests itself through two "steps" in the graph. The first step corresponds to the theoretical value of the medium access time without queuing, the second and third steps indicate 1 or 2 reservation cycles of queuing delay.

This behaviour can be considered as a point of future optimization. Even so the B-AMC DLL performs very well and gives opportunities to respect not only DLL specific performance issues, but also physical layer aspects (i.e. BAMC TX duty cycle optimization).

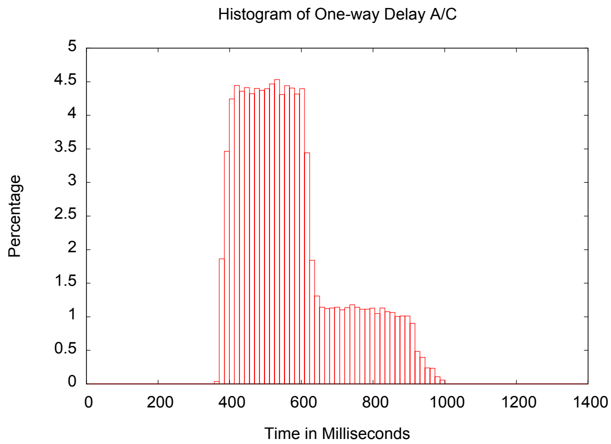

FIG 10. Histogram of one-way delay for scenario ENR large – Reverse Link (RL).

6. ASSESSMENT AND CONCLUSION

For adapting the B-VHF system to L-band conditions several changes of the physical layer design are required including the duplex scheme, access scheme, framing structure, and OFDM system parameters. Simulations with the revised physical layer design confirm the assumption of 500 kHz bandwidth being available between two adjacent DME channels. Moreover, a good performance is achieved in presence of interference from DME systems operating in adjacent channels. The performance can be further improved by estimating if a interferer is present or not and taking into account this information in the detector and decoder. Consequently, the B-AMC system can be operated in the L-band if its centre frequencies are selected properly such as to keep interference from DME stations at a minimum.

The adapted MAC layer briefly presented in this document introduced determinism for the medium access latency, which is significant for aeronautical safety related applications. The reservation cycle preserves fairness and guarantees a minimum bandwidth among all users. This bandwidth is dependent on the amount of users currently registered to one cell.

Considering the asynchronous data traffic (i.e. RL data capacity requirements are less than FL data capacity requirements) the RL medium access latency can be further reduced by a factor of 2 by introducing additional signalling opportunities. This results in a very low latency data link even if many A/C joined a single cell.

Due to the expected interference of the DME a significant overhead of coding had to be introduced to guarantee a reasonable data link capacity, still the selected 500 kHz are enough to support the ENR large scenario requirements from the COCR study [8].

7. REFERENCES

[1] M. Schnell, E. Haas, M. Sajatovic, C. Rihacek, B. Haindl, "B-VHF – An Overlay System Concept for Future ATC Communications in the VHF Band", in *Proceedings of 23rd IEEE/AIAA Digital Avionics Systems Conference (DASC 2004)*, Salt Lake City, Utah, USA, October 2004, pp. 1.E.2-1 - 1.E.2-9.

[2] I. Cosovic, S. Brandes, M. Schnell, B. Haindl, "Physical Layer Design for a Broadband Overlay System in the VHF Band With In-band Transition", in *Proceedings of the 24th Digital Avionics Systems Conference (DASC 2005)*, Washington, D.C., USA, October/November 2005, pp. 1.C.1-1 – 1.C.1-10.

[3] S. Brandes, M. Schnell, C.-H. Rokitansky, M. Ehammer, Th. Gräupl, H. Steendam, M. Guenach, C. Rihacek, and B. Haindl, "B-VHF - Selected Simulation Results and Final Assessment," in *Proc. 25th Digital Avionics Systems Conf. (DASC 2006)*, Portland, OR, USA, October 2006.

[4] EUROCONTROL/FAA Future Communications Study, Operational Concepts and Requirements Team, "Communications Operating Concept and Requirements for the Future Radio System," Ver. 2, May 2007.

[5] B-VHF project, "B-VHF Functional Principles and Architecture," report D-06, project number AST3-CT-2003-502910, Issue 1.0, 05.04.2005

[6] B-VHF project, "MAC Requirements and Specification," report D-19, project number AST3-CT-2003-502910, Issue 1.0, 25.05.2005

[7] http://www.b-vhf.org

[8] EUROCONTROL/FAA Future Communications Study, Operational Concepts and Requirements Team, "Evaluation Scenarios," 2007.

[9] EUROCONTROL, "VDL Mode 2 Capacity Analysis through Simulations: WP3.B – NAVSIM Overview and Validation Results", Edition 1.2, 31.10.2005.

[10] S. Brandes, S. Gligorevic, M. Schnell, C.H. Rokitansky, M. Ehammer, T. Gräupl, A. Schlereth, C. Rihacek, „Final Assessment of the B-VHF Overlay Concept" IEEE Aerospace Conference, Big Sky, MT, USA, Mar. 03-10, 2007.