B-AMC – Broadband Aeronautical Multi-carrier Communications

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Abstract

The Broadband Aeronautical Multi-carrier Communications (B-AMC) system is a promising candidate for the future L-band radio system called L-band Digital Aeronautical Communications System (L-DACS). In this paper, the design of the physical (PHY) as well as of the data link layer (DLL) is addressed. As B-AMC is intended to be operated in the L-band between two adjacent distance measuring equipment (DME) channels, the avoidance of mutual interference between existing L-band systems and B-AMC has been in the focus of the PHY layer design. In order to demonstrate the feasibility of the coexistence with DME, a draft frequency planning has been performed for Europe, resulting in successful frequency assignments in wide parts of Europe. The B-AMC DLL supports data link communication with low latency and high throughput. It is designed to be highly configurable and to support different service requirement sets and traffic profiles. In this paper, the current DLL configuration featuring a low RL duty-cycle and graceful degradation is discussed in detail.

Introduction

B-AMC is one of the technologies proposed for the future L-DACS. It is based on the B-VHF (Broadband VHF) system concept [1,2] developed from 2004 to 2006 within the B-VHF project co-funded by the European Commission. The joint Eurocontrol/FAA Future Communications Study (FCS) selected B-VHF as one of the most promising technologies and put it on the technology shortlist. As recent developments have shown that the future air-ground (A/G) communications system will more likely be deployed in the L-band (960-1164 MHz), Eurocontrol initiated the redesign of B-VHF for L-band useage. As final result of the FCS, B-AMC has been chosen as a candidate for the broadband L-DACS solution, together with the P34 system [3]. The second L-DACS option is based on narrowband technologies.

The B-AMC system has been designed to support A/G as well as direct air-air (A/A) communication without using a ground relay station. These two communication capabilities are realized as two separate modes. In this paper, only the A/G mode is considered. When designing the B-AMC system, emphasis has been put on supporting data communications. However, voice communication is still available as a configurable option. The B-AMC A/G mode covers all Air Traffic Services (ATS) and safety-related Aeronautical Operational Control (AOC) communications services. The service requirements, as defined in the Communications Operating Concepts and Requirements (COCR) document [4], have been considered in the B-AMC design to provide the capacity for future ATC communications of 2020 and beyond.

The B-AMC system is a broadband multi-carrier system using Orthogonal Frequency-Division Multiplexing (OFDM). It is intended to be operated as an inlay system, in the spectral gaps between two adjacent DME channels. Therefore, in contrast to other L-DACS proposals, B-AMC does not require any "green" spectrum. However, the B-AMC receiver is exposed to partly severe interference originating from systems currently deployed in the L-Band such as DME, SSR/Mode S, the military Joint Tactical Information Distribution System (JTIDS), and UAT. In addition, high modulation sidelobes that are characteristic for OFDM systems have to be sufficiently reduced at the B-AMC transmitter in order not to disturb already existing L-band systems. These new interference and propagation conditions in the L-band have required several adaptations of the B-AMC PHY layer as compared to the B-VHF PHY layer design.

The redesign of the PHY has necessitated a radical revision of the higher layer protocols as well. Key design objective of the new protocol stack was optimizing data communications while optionally supporting digital voice. For A/G communications, an enhanced DLL design has been derived, that is optimized for data transfer, allowing configurable resource allocation. A deterministic medium access control (MAC) algorithm has been introduced to provide a stable and predicable data link for safety-related data communication. In the current configuration, the B-AMC DLL resource allocation mechanism puts strong emphasis on low latency and low airborne transmitter utilization factor (e.g. low duty cycle) in order to alleviate co-site interference towards other airborne L-band receivers.

The remainder of this paper is basically subdivided into two parts. In the first part, the design of the B-AMC PHY layer is addressed. Taking into account mutual interference between DME and B-AMC, a first draft frequency planning for Europe has been performed in order to demonstrate the feasibility of the inlay deployment concept. The second part is dedicated to the architecture of the DLL. It is shown that B-AMC is capable of fulfilling the requirements of the future aeronautical A/G communication system. Finally, conclusions are drawn and an outlook on future activities is given.

PHY Layer

The PHY layer for the B-AMC A/G mode is designed such as to cope with L-band conditions characterized by high Doppler frequencies and strong interference from legacy L-band transmitters. B-AMC is constructed as an inlay system, i.e. it is intended to be operated between two adjacent DME channels as illustrated in Figure 1. Hence, B-AMC virtually requires no additional spectrum and allows the existing DME channel allocation to remain unchanged. However, this implies that the B-AMC system must not interfere with existing DME stations, and itself must tolerate severe interference from DME and other L-band systems.

Design and System Parameters

It is assumed that the B-AMC system uses channels with 500 kHz bandwidth placed between two adjacent DME channels for each forward and reverse link (FL/RL). This bandwidth is used by an OFDM system with 48 subcarriers, resulting in a subcarrier spacing of 10.416 kHz that is sufficient to compensate a typically occurring Doppler spread

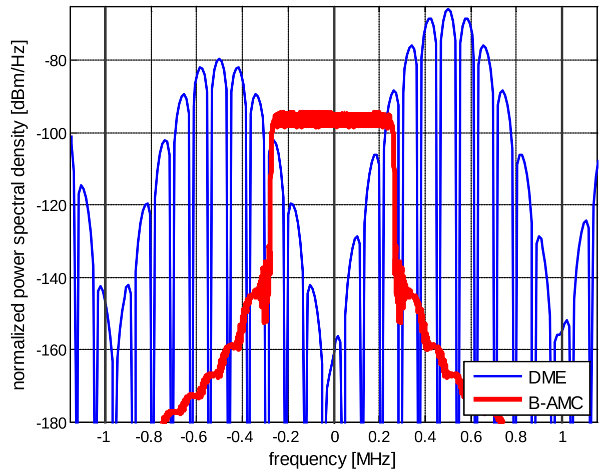

Figure 1: Spectrum of B-AMC signal between two adjacent DME channels.

of up to about 1 kHz. For OFDM modulation, a 64-point FFT is used. According to the subcarrier spacing, one OFDM symbol has a duration of 96 µs. Each OFDM symbol is extended by a cyclic prefix as long as 24 µs, comprising a guard interval of 12 µs for compensating multipath effects as well as 12 µs for TX windowing for reducing out-of-band radiation. 54 successive OFDM symbols are organized into one OFDM frame, resulting in a frame duration of 6.48 ms. Each frame contains 48 OFDM symbols for transmission of payload data. The remaining 6 OFDM symbols are used as synchronization symbols (required in the FL) and pilot symbols for channel estimation (required in both FL and RL). The main system parameters are summarized in Table 1. For more details please refer to [5, 6].

Table 1: Main B-AMC system parameters.

Parameter	**Value**
Effective bandwidth (FL or RL)	500 kHz
Sub-carrier spacing	10.416 kHz
Used sub-carriers	48
FFT length	64
OFDM symbol duration	96 µs
Cyclic prefix	24 µs
Total OFDM symbol duration	120 µs
OFDM symbols per frame	54
Data OFDM symbols per frame	48
OFDM frame duration	6.48 ms

B-AMC FL and RL are separated by frequency-division duplex (FDD). In FL, pure OFDM is used and data is transmitted to different users on a packet-switched basis. In RL, different users are separated by a combination of orthogonal frequency-division multiple access (OFDMA) and time-division multiple access (TDMA). Within one frame, different subcarriers or sets of subcarriers are assigned to different users. In addition, different airborne users are separated in time by assigning different subcarrier sets in different frames to different users.

For organizing multiple access, dedicated OFDM signaling frames exist apart from conventional OFDM data frames. One FL broadcast (BC) frame consists of 56 OFDM symbols and, therefore, has a frame duration of 6.72 ms. The BC frame comprises three sub-frames and is used in FL to announce common ground station (GS) information to all aircraft within GS range. Aircraft in neighboring B-AMC cells can also synchronize and listen to it in order to prepare cell handovers. The random access (RA) frame used in RL provides net entry opportunities for newly arriving aircraft. Two short RA frames appear within one RA slot. The duration of the RA slot is the same as that of the BC frame, i.e. 6.72 ms. The RA slot in the RL is aligned in time with the BC frame transmitted in the FL.

Coding and modulation are chosen such as to make the transmitted B-AMC signal robust towards interference. For forward error correction (FEC) coding, a concatenation of a convolutional and a Reed-Solomon code with total code rate 0.45 is employed. With modulation schemes ranging from QPSK used for strong interference conditions to 64-QAM for weaker interference conditions, data rates from 270 kbit/s to 1.3 Mbit/s are provided.

In case strong DME interference occurs, nearly all subcarriers of an OFDM symbol are affected. Hence, it is advantageous to encode the bits contained in one OFDM frame in time direction, i.e. orthogonal to the frequency direction where interference occurs. As inner code, a convolutional code is applied. After decoding, interference hits will leave burst errors that can be corrected by the outer Reed-Solomon code in most cases.

At the B-AMC receiver, the subcarriers and OFDM symbols impaired by interference can easily be identified by observing interference power on the unmodulated OFDM subcarriers in the guard band at each side of the B-AMC spectrum. The values on the affected subcarriers are erased at the input of the decoder in order to not provide the decoder with wrong information. With this method referred to as interference-adjusted decoding, significant performance improvements are achieved as will be demonstrated in the next section.

Interference

The B-AMC inlay concept demands the minimization of mutual interference between B-AMC and other L-band systems. Special emphasis has to be put on the coexistence between B-AMC and DME systems, which is especially challenging due to the very small possible separation in frequency, i.e. only 0.5 MHz.

Interference from DME to B-AMC

For evaluating the impact of DME interference on the B-AMC system the DME signal has to be modeled as realistically as possible. In the interference simulator, for each contributing DME station, Gaussian-shaped pulse pairs are generated and modulated onto a L-band carrier frequency at an adjustable offset relative to the B-AMC center frequency. That way, interferers in arbitrary DME channels and an arbitrary number of DME stations per channel can be considered. The further processing of the DME interference in the B-AMC receiver is the same as for the B-AMC signal, i.e. RX filtering, oversampling, and the FFT are applied in order to finally obtain the interference contribution to each subcarrier.

The impact of DME interference in the FL is simulated for an interference scenario representing severe interference conditions. As the B-AMC FL is intended to be operated in the sub-band 985-1009 MHz, except for the “own” airborne DME interrogator, only DME GSs cause interference at the B-AMC airborne receiver. The real DME channel allocation is modeled with the NAVSIM[1] tool [7] for the area around Paris as this is the area with the highest density of DME GSs in Europe. The victim B-AMC receiver is positioned at an en-route (ENR) flight level at 45,000 feet altitude in the center of

[1] The Air Traffic / ATC & CNS simulation tool "NAVSIM" has been developed by "Mobile Communications R&D GmbH, Salzburg" in close co-operation with University of Salzburg.

this area. The peak interference power originating from each DME/TACAN station is determined via simple link budget calculations, taking into account free space loss and antenna patterns dependent on elevation angles. Severe interference conditions are observed when the B-AMC system is operated at 995.5 MHz. A strong interferer occurs in the channel at 995 MHz. Due to the large received power levels, the pulse rates of the two interferers operating at 996 MHz effectively superimpose, such that almost each OFDM symbol is affected. At 994 and 997 MHz, multiple interferers occur. However, due to their larger frequency offset, they do not impair the B-AMC system significantly. The considered interference scenario is listed in Table 2.

In the simulations, 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 modeled by an appropriate channel model adapted to the L-band taking into account Doppler effects resulting from high aircraft velocities, a strong line-of-sight component, and one delayed path. The receiver noise level N_0 is kept constant at -165 dBm/Hz, taking into account thermal noise with density -174 dBm/Hz and assuming 9 dB receiver noise figure. The power of the interferers is chosen according to the interference scenario from Table 2. E_b/N_0 at the B-AMC receiver is varied in order to be able to determine the power required to receive and decode the B-AMC signal with a certain quality.

Table 2: Interference scenario, ENR, FL.

Station	Frequency [MHz]	Interference power at victim RX input	Pulse rate (ppps)
TACAN	994	-72.4 dBm	3600
TACAN	994	-74.0 dBm	3600
TACAN	994	-88.2 dBm	3600
TACAN	995	-67.9 dBm	3600
B-AMC	995.5		
TACAN	996	-74.0 dBm	3600
TACAN	996	-90.3 dBm	3600
DME	997	-81.6 dBm	2700
DME	997	-86.5 dBm	2700
DME	997	-85.7 dBm	2700
DME	997	-88.1 dBm	2700
DME	997	-82.5 dBm	2700
TACAN	997	-68.9 dBm	3600

In Figure 2, the frame error rate (FER) for the FL is shown for different decoding schemes. Compared to the interference-free case, in case of interference, performance is degraded by about 25 dB, when conventional decoding is applied. Significant improvements are achieved with interference-adjusted decoding, when a fixed number of subcarriers is erased in an affected OFDM symbol. However, due to the many interfering DME stations with different power it happens that in some OFDM symbols too few, whilst in other OFDM symbols too many subcarriers are erased. Consequently, the approach, where the number of subcarriers to be erased is adapted according to the observed interference power, performs considerably better. In that case, the gap between the interference-free case and the performance achieved with interference reduces to 5 dB even for the considered severe interference conditions. With adapted erasures, E_b/N_0 = 8 dB is required for providing FER = 10^{-2} as required by the B-AMC DLL. For a cell size of 120 nm this translates to a B-AMC minimum transmit power of 35.5 dBm which is a reasonable value, even with respect to interference onto DME and other L-band systems.

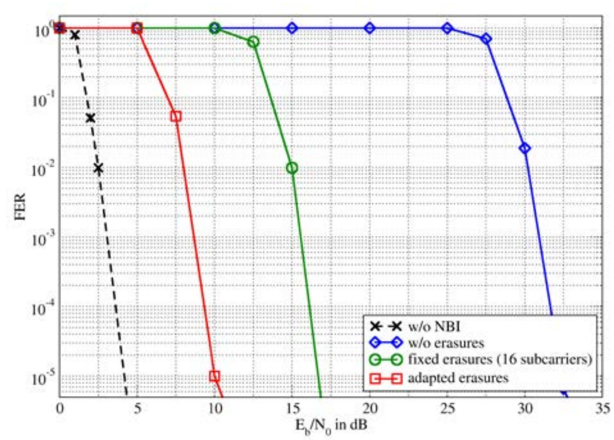

Figure 2: E_b/N_0 vs. FER, FL, en-route scenario.

Interference from B-AMC to DME

In order to reduce interference onto existing L-band systems, so-called cancellation carriers are inserted at both edges of the B-AMC spectrum adjacent to the outmost modulated OFDM subcarriers. The two cancellation carriers at each side carry complex weighting factors that are optimized such that the sidelobes of the cancellation carriers cancel the sidelobes of the original OFDM signal. This technique has already been proposed for B-VHF [2] and provides a significant reduction of out-of-band radiation in the frequency range close to the B-AMC bandwidth. Since sidelobes have to be reduced also in the outer areas of the spectrum, TX windowing is applied in addition. The time domain TX signal is multiplied with a windowing function that differs from the normally applied rectangular window. Since the spectrum of the windowing function has lower sidelobes than the si-function corresponding to the rectangular window, spectral characteristics of the complete transmitted OFDM signal are improved. However, in order to maintain subcarrier orthogonality, the length of the cyclic prefix has to be increased. The additional cyclic prefix has already been considered in the B-AMC parameters from Table 1, allowing for applying a raised-cosine window with 10% roll-off. The resulting spectra are shown in Figure 3. Compared to the OFDM signal without utilization of any sidelobe suppression technique, a significant reduction of out-of-band radiation is observed.

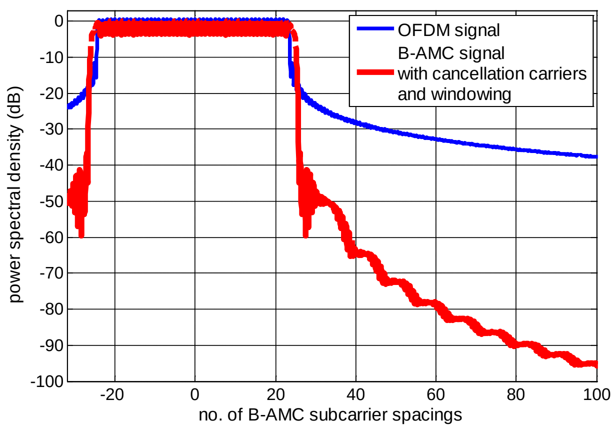

Figure 3: Spectrum of B-AMC signal with reduced sidelobes.

From the simulated TX spectrum, a first approximation of a spectral mask for B-AMC can be derived. Other effects such as phase noise and third order intermodulation products are taken into account as well. Based on this spectral mask, the impact of the B-AMC TX signal onto any other system operating at a different frequency can be derived. With the so-called frequency dependent rejection (FDR) method [8], the degree of rejection of undesired B-AMC transmitter energy by a victim (e.g. DME) receiver is determined taking into account the fact that not all of the undesired transmitter energy at the victim receiver input will be available at the detector. The required inputs for this method are the power spectral density of the interfering signal represented e.g. by the B-AMC spectral mask as well as the frequency response of the victim (e.g. DME) receiver.

Initial Frequency Planning

In order to demonstrate the feasibility of the B-AMC inlay concept, it is checked if in each part of Europe center frequencies for B-AMC ENR cells can be found that allow for a successful coexistence of DME and B-AMC. As the B-AMC system is an inlay system, the conventional approach for frequency planning that takes into account the allowed desired-to-undesired signal ratio at the victim receiver operating in the same or an adjacent channel could not be applied. Instead, a different approach is pursued. In the draft frequency planning, only two important interference cases are considered, namely the protection of airborne DME receivers from ground B-AMC transmitters and the protection of airborne B-AMC receivers from ground DME transponders. Therefore, only FL channels in the sub-band 979-1019 MHz are considered, whereas B-AMC RL channels are assumed to be assigned at a fixed offset of 63 MHz above FL channels.

In order to guarantee that the B-AMC GS does not disturb an airborne DME receiver, the level of interference power the B-AMC signal causes at the closest possible DME airborne receiver operating at ±0.5, ±1.5, or ± 2.5 MHz offset is determined and compared to the threshold of tolerable noise-like interference power. With a simple link budget analysis, the amount of interference power at the input of the victim DME receiver is calculated assuming 38 dBm TX power for the B-AMC GS. The FDR values have been calculated from the expected B-AMC TX spectrum and a representative selectivity curve for the DME victim receiver derived from standard commercially available DME equipment. The results for frequency offsets between B-AMC and DME systems of ±0.5, ±1.5, or ±2.5 MHz are listed in Table 3.

The level of tolerable interference power is determined based on the protected desired DME signal value at the DME airborne RX antenna [9].

Considering antenna cable losses, the reference airborne antenna gain (5.4 dBi), a desired-to-undesired signal ratio of 16 dB [10], 6 dB aeronautical safety margin and another 6 dB multiple-system margin [11], the threshold of tolerable interference power at the input of the DME receiver has been set to -106.6 dBm. This is a conservative, but typical assumption for aeronautical systems, since large margins have been considered.

When the received interference power in all six adjacent DME channels at ±0.5, ±1.5, and ±2.5 MHz offset is below the threshold, the investigated frequency is a candidate for a B-AMC center frequency.

Table 3: FDR for interference from B-AMC GS to airborne DME receiver.

Offset Δf	± 0.5 MHz	± 1.5 MHz	± 2.5 MHz
FDR (Δf)	-0.93 dB	-45.88 dB	-68.36 dB

Once possible candidate center frequencies are identified, it has to be checked whether or not interference at airborne B-AMC receivers originating from ground DME transponders is tolerable. As the level of tolerable interference power could not be determined so far, the expected FER is used as decision criterion, i.e. the center frequency is a suitable candidate when the expected FER is below 10^{-2} under interference conditions in the considered cell.

The airborne B-AMC victim receiver is positioned within an area around the B-AMC GS with 120 nm radius. The exact position within the cell is selected such as to expose the victim receiver to worst case interference conditions in the directly adjacent channels. Systematic interference investigations with different power levels and pulse rates have shown that an interference constellation with multiple interferers can be represented (as a worst case) by a simplified constellation with only one interferer in each adjacent channel with both interferers each having the same representative power and pulse rate. After applying this simplification to the currently observed interference conditions, the expected FER can be derived from the available simulation results. Depending on the obtained expected FER, the investigated center frequency is either retained or removed from the candidate list.

Taking into account a reuse distance factor of 4.56 for B-AMC cells, B-AMC center frequencies could be found for large parts of Europe. However, for some cells within the core area, no frequencies could be assigned as either the interference from DME to B-AMC or vice versa was too high. In a second refinement step, the B-AMC cell size has been reduced from 120 nm to 60 nm in the critical areas. The B-AMC TX power has been reduced correspondingly, hence improving interference conditions for DME receivers as well as for B-AMC receivers, since for smaller cells less DME stations have to be considered. The resulting draft frequency plan for Europe with mixed 120 nm/60 nm cells is given in Figure 4. Cells with green borderline indicate that a B-AMC frequency could be assigned taking into account the most stringent threshold of tolerable interference power at a DME airborne receiver (-106.6 dBm). For some areas, especially in core Europe with high density of DME stations, this threshold would have to be relaxed by 6 dB in order to find an appropriate B-AMC frequency (yellow borderlines). However, this preliminary result has been derived under worst case assumptions. The situation is expected to further improve with more realistic assumptions, e.g. with respect to tolerable interference for DME.

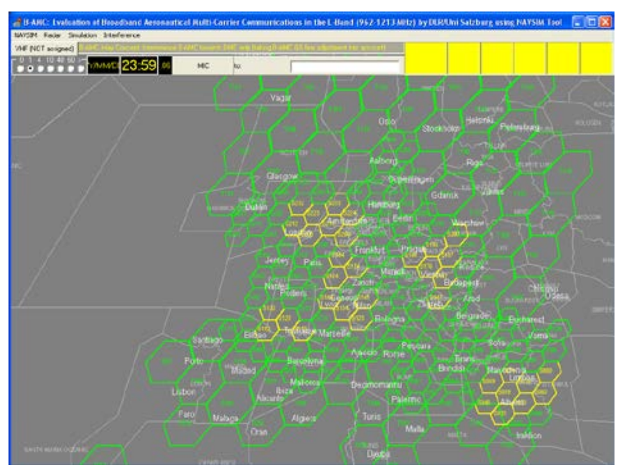

Figure 4: Possible B-AMC ENR cells for Europe, 60 or 120 nm cell radius.

Data Link Layer

The B-AMC DLL comprises two sub-layers, the MAC sub-layer and the Logical Link Control (LLC) sub-layer, and five major entities. These entities are inter-connected via internal channels, which are described later in this section. The overall structure of the B-AMC DLL is illustrated in Figure 5.

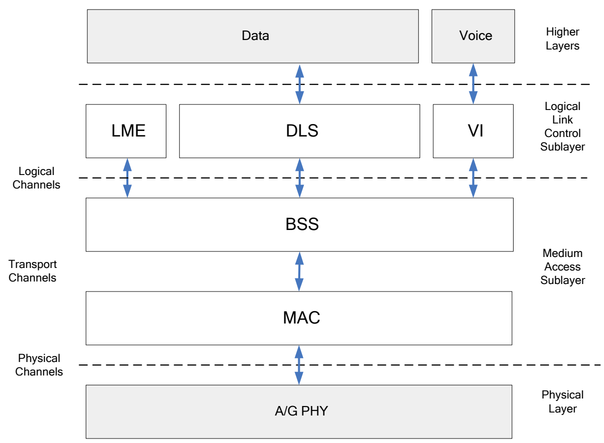

Figure 5: B-AMC protocol stack in A/G mode.

Functional Entities

The LLC sub-layer of the DLL manages the radio link and offers a bearer service with different levels of Quality of Service (QoS) to the higher (sub-network) layer. It is up to the LLC layer to achieve the required final level of data integrity (at layer 2) and to support priorities between QoS classes by mapping higher layer packets to appropriate DLL logical channels. The LLC contains the Link Management Entity (LME), the Data Link Services (DLS), and the Voice Interface (VI).

The B-AMC DLS entity of the LLC is intended to provide several levels of QoS with different classes of service (CoS). Where the required integrity of a traffic class cannot be achieved using the FEC of the PHY layer alone, the DLS improves integrity using Automatic Repeat Request (ARQ) protocol and checksums. The DLS uses the logical *data channel* DCH for user plane transmissions and the logical *dedicated control channel* DCCH for control plane transmissions (e.g. ARQ acknowledgements).

The B-AMC Link Management Entity (LME) functionality comprises the B-AMC system procedures supporting net-entry, net-exit, handover, etc. During net-entry, LME uses for signaling the logical *broadcast control channel* BCCH and the logical *random access channel* RACH. During normal operations, it uses the logical *common control channel* CCCH, the logical *synchronized access channel* SACH and DCCH.

The medium access sub-layer comprises the B-AMC Special Services (BSS) entity and the MAC entity. The BSS entity provides the transport service to the DLS mapping logical channels to transport channels. It provides a sending and a receiving buffer for each transport channel and injects or extracts data link frames (data link layer - protocol data units; DLL-PDUs) from the transport channels. Each DLL-PDU received from the LLC sub-layer is put into the BSS queue corresponding to the type of service it intends to use. Note that due to time constraints only one queue (i.e. service class) has been implemented for the DCH in the evaluation presented in this paper. Whenever the BSS is granted a transport channel by the MAC entity (using the resource acquisition mechanism described below) the content of the queue (or a part of it) is injected into the granted transport channel.

The MAC entity maps transport channels to the physical channels provided by the PHY layer of the radio link. For RL transmissions the transport channel capacity is requested by the airborne MAC entity and is then allocated by the GS.

Channel Structure

Each of the B-AMC DLL protocol sub-layers provides services to upper sub-layers. The services are offered in the form of communication 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, and Voice Interface) via logical channels. Each logical channel type is defined by the type of information which is transferred. B-AMC logical channels can be classified into control channels (e.g. BCCH, RACH, SACH, DCCH, and CCCH) for the transfer of control plane information and traffic channels (e.g. DCH and VCH) for the transfer of user plane information.

Transport channels - The MAC sub-layer provides data transfer services to the BSS sub-layer via transport channels. Transport channels provide the MAC sub-layer with an abstraction of PHY layer OFDM frames. A set of transport channel types (*TBC, TRA, T1, T2,…,T48*) is defined for different kinds of data transfer services. In the RL, different types of transport channels with different transmission bandwidths are realized by assigning an appropriate number of *n* distinct OFDM sub-carriers to a particular user (i.e. particular aircraft). This is reflected in the transport channel type *Tn* where *n* ranges from 1 to the maximum number of useable subcarriers which is 48, i.e. *n*= 1,…,48. Other aircraft may simultaneously use a distinct set of RL OFDM sub-carriers (there may be multiple RL links in parallel). In the FL, the GS uses all 48 subcarriers all the time. The actual mapping of transport channels to physical channels (i.e. sub-carriers of OFDMA frames) is performed by the PHY layer. Sizes and capacities for an exemplary set of transport channel types are displayed in Table 4. Note, that the data rates in FL and RL differ due to the multi-frame structure (explained below). The RL requires more signaling overhead.

Table 4: Exemplary transport channel definition for T48, T24, T12, T6, T3.

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				

While the mapping of logical control channels (BCCH, RACH, SACH, DCCH, and CCCH) onto transport channels is fixed, the logical traffic channels (DCH, VCH) may be mapped onto various types of transport channels, dependent on the required bandwidth. The MAC frame structure and resource acquisition mechanism is discussed below.

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

Frame Structure

The B-AMC medium access sub-layer uses the framed structure provided by the PHY layer to create its own slotted time structure (MAC framing). 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 ms = 58.32 ms) each containing one OFDM frame, see Figure 6. All FL frames (also all RL frames) in a MF have the same structure, but may convey different information.

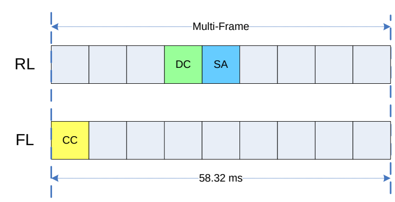

Figure 6: B-AMC slot structure – Multi-Frame.

On the FL, the first slot (Common Control (CC) slot) of each multi-frame is used for a *T48* transport channel carrying the logical Common Control Channel (CCCH). The main purpose of the CCCH is to assign - upon request - RL transport channels to different aircraft. The remaining 8 slots of the FL multi-frame are used for the transmission of eight *T48* transport channels containing the logical channels of the user plane (user's voice and data).

On the RL, there are 7 data slots and two special purpose slots per multi-frame. The Synchronized Access (SA) slot is used for SACH where only "low-bandwidth" *T1* transport channels are used (48 per slot). At net entry, each aircraft is assigned one *T1* transport channel (i.e. single RL OFDM sub-carrier), thus the system provides to each of up to 48 aircraft a dedicated low bit-rate transport channel for its SACH. If the number of aircraft exceeds 48, the SACH assignments are distributed over the SA slots of several MFs using TDMA in a round-robin manner. The Dedicated Control (DC) slot has the same structure as the SA slot and uses the same assignment policy (using TDMA for more than 48 users). It is used to provide each aircraft with a dedicated low bit-rate transport channel for its logical Dedicated Control Channel (DCCH), which conveys LLC signaling information. 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) between incoming and outgoing messages.

In order to build the B-AMC super-frame (SF), four MFs are grouped together and prepended by one Random Access (RA) slot for the RL and one Broadcast (BC) slot for the FL. The super-frame has an overall length of

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

The B-AMC super-frame structure is illustrated in Figure 7.

The RA slot conveys the *TRA* transport channel / RACH logical channel. Similarly, on the FL the BC slot conveys a *TBC* transport channel / BCCH logical channel. On the PHY layer this corresponds to one RA OFDM frame followed by four MFs (36 conventional data frames) on the RL, and one broadcast frame followed by four MFs (36 conventional data frames) on the FL. These channels are only used during net-entry and hand-over.

Multiple Access

The B-AMC system uses FDD with separated FL and RL channels to provide full-duplex communication. Since the FL is exclusively used by the GS, no multiple access scheme is required in this direction. The GS directly allocates FL resources and manages access priorities of external competing services/users. On the RL a combination of TDMA and OFDMA is used to provide a particular aircraft with access to the shared RL medium. RL access is arbitrated by a contention-free resource reservation algorithm. This algorithm is implemented in the GS MAC resource allocation function, managing the assignment of RL slots and transport channels. It has been designed to provide "hard" QoS in a deterministic way.

In order to acquire communications resources, each aircraft has to report its resource needs to the ground-station in advance via the SACH logical channel. On the basis of these reports, the GS will allocate RL resources via the FL CCCH logical channel. The resource request and assignment procedure is shown in Figure 8 (assuming less than 48 airborne users). For more than 48 users, the cycle extends over an appropriate number of MFs.

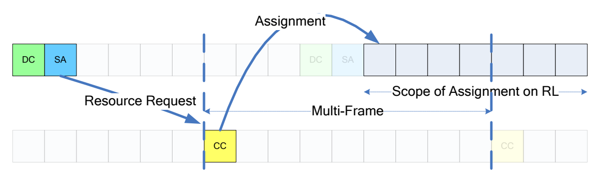

Figure 8: Structure of the RL resource request and assignment procedure.

The RL request cycle denotes the time needed to process the resource request of all aircraft within a cell. The average length of the request cycle grows linearly with the number of mobile users providing each with one dedicated resource request

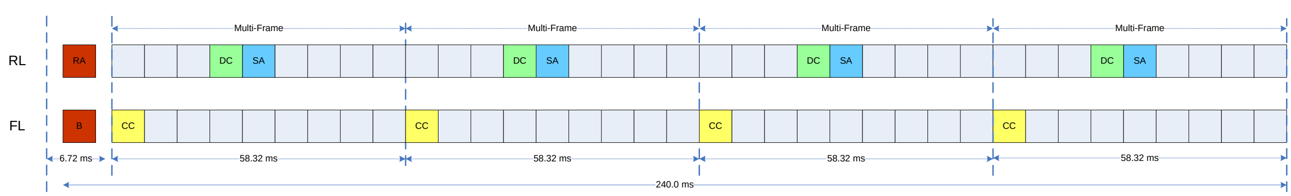

Figure 7: B-AMC Super-Frame structure

grows linearly with the number of mobile user providing each with one dedicated resource request opportunity per cycle.

RL Resource Allocation

Although the structure of the resource request cycle is fixed, the modus of the RL resource allocation may be freely configured. For the purpose of system performance investigations, the resource allocation algorithm has been chosen such as to provide a low airborne duty cycle (to reduce co-site interference towards other airborne systems) and to behave in a very stable and predictable way (a desirable feature for a safety-related aeronautical system). The algorithm is defined as follows:

1. Resource requests of all aircraft logged into the cell are collected during one request cycle.
2. When all requests of the cycle are known, a fair resource allocation can be performed. Resources are assigned to each aircraft in the next request cycle in exactly the same order as they have been collected.
3. In order to ensure low airborne duty cycle, resource allocations are limited to one T24 transport channel (1013 bit) per cycle and aircraft.

This channel size has been chosen, as the majority of the messages defined in [4] can be conveyed in one such channel within a single RL data frame.

Medium Access Performance

The performance of the B-AMC medium access sub-layer, as presented in this paper, has been studied using a Markovian traffic model. The communication traffic was generated by a Poisson process with rate λ and a constant packet size of 1013 bit. λ is determined according to the traffic load under investigation.

Considering the resource allocation algorithm of the last section and assuming that the B-AMC MAC sub-layer is not operated near to saturation (i.e. less than 95% of the maximum capacity is effectively used, which is approximately 225 kbps of RL load), the system performance can be characterized by a simple formal model. In this case the medium access latency is mainly determined by the resource allocation process and MAC queuing.

The latency of the resource allocation process depends on the length of the request cycle. If resource requests are uniformly distributed within the request cycle, an aircraft will, on average, have to wait for a half of a reservation cycle until its request is collected (step 1 of the algorithm). Once the request has been received, it takes exactly one cycle until the resource is assigned (step 2). The average length of the resource allocation process is thus *1.5* l_{rc}. The average length of the request cycle l_{rc} is determined by

$$l_{rc} = \frac{n}{N_{c,used}} 60.0\,ms,$$

where the number of aircraft logged into the cell is denoted with n and $N_{c,used}$ denotes the number of usable subcarriers (48).

On the basis of the average service time of the resource allocation process, the B-AMC MAC sub-layer can be described as a queuing system. As the service time is not necessarily distributed according to a common probability distribution, an M/G/1 queuing model is needed to correctly determine the average waiting time $W_{M/G/1}$ of MAC-PDUs in the TX queue. The average MAC latency is then the sum of the average length of the resource allocation process, the average waiting time in the TX queue and the transmission time of the packet:

$$t_{MAC}(n,\lambda) = 1.5\,l_{rc}(n) + W_{M/G/1}(n,\lambda) + t_{TX},$$

where t_{TX} denotes the transmission time. Note that under light load the queuing delay is small in comparison to the length of the request cycle and can therefore be ignored. Thus,

$$t_{MAC}(n) \approx 1.5\,l_{rc}(n) + t_{TX} = \frac{3\,n}{2\,N_{c,used}} 60.0\,ms + 6.48\,ms$$

is a good approximation for the RL MAC latency. Figure 9 displays the performance of the RL MAC at a load of 40 kbps (a typical value from [4]) dependent on the aircraft population. Obviously, the formal model $t_{MAC}(n,\lambda)$ describes the actual system behavior very well.

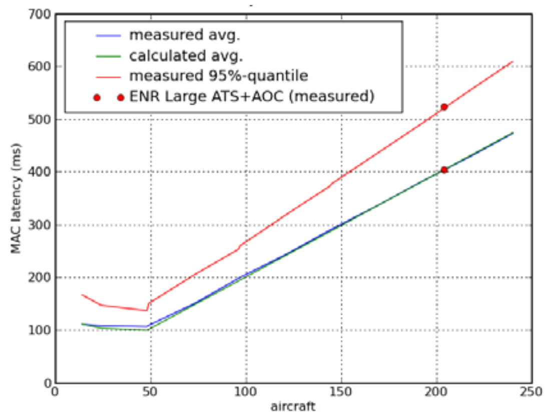

Figure 9: RL MAC latency as a function of the number of aircraft.

Note that the average performance of the system degrades linearly. B-AMC therefore exhibits a built-in graceful performance degradation. The system behavior remains predictable at all times. In addition, the presented resource allocation process is extremely fair. It achieves 99.80% fairness according to Jain's fairness index.

Overall System Performance

The overall performance of the B-AMC system has been determined according to the evaluation scenarios defined jointly by EUROCONTROL and FAA in [12] that in turn were derived from [4]. Within this paper only one representative result is presented in detail. Further results are discussed in [5, 6].

Table 5 displays the results (throughput, average latency) for the En-Route Large scenario (204 aircraft, ATS and AOC traffic combined, no A-EXEC) under the described traffic model. Note that the results below include the effects of the LLC sub-layer ARQ protocol. The plain MAC performance (not taking LLC-ARQ into account) is indicated in Figure 9 with red dots (average RL latency and 95%-quantile of RL MAC latency).

The RL duty cycle of this scenario was only 1.56 % per aircraft. It is worth noting that above results fully satisfy the requirements for the Future Radio System (FRS) stated in [4] for the corresponding scenario. Moreover, the results have been achieved via simulations without having implemented QoS management anticipated in the B-AMC design (prioritizing of incoming RL requests by the GS dependent on the required QoS). Once the QoS support becomes available within the real B-AMC system, the results may further improve significantly.

Table 5: Overall performance: En-Route Large, combined ATS and AOC traffic, 204 aircraft.

	FL	RL	Required TD_{95}
Throughput	220.02 kbps	44.01 kbps	
Average latency	26 ms	531 ms	1400 ms
95%-quantile of latency (**TD_{95}**)	39 ms	833 ms	1400 ms

Conclusions and Outlook

In the first part of this paper, the design of the B-AMC PHY layer has been presented. FER simulations for the FL have shown that the B-AMC system performs well under severe interference conditions, using the decoding algorithm adapted to the observed interference conditions. This algorithm is being further refined in order to reduce the existing performance gap between the cases with and without interference. In addition, it has been shown, that out-of-band emissions of the B-AMC transmit signal can be significantly reduced by means of the sidelobe suppression techniques. Based on these investigations, a first draft frequency planning for Europe has been performed. For each of about 200 B-AMC ENR cells with 120 nm radius each, an attempt was made to allocate B-AMC FL channels such that neither the B-AMC GSs disturb DME airborne receivers nor the B-AMC airborne receiver is disturbed by DME GSs operating in adjacent channels. Although based on worst case assumptions, B-AMC center frequencies could be found for most areas in Europe. In future work, the frequency planning procedure will be refined in order to assign appropriate frequencies explicitly for the whole area of Europe.

For a more reliable assessment of mutual interference between DME and B-AMC systems and a definition of definitive frequency planning criteria, B-AMC prototypes have to be built. Then, laboratory tests have to be carried out, aiming at a final definition of tolerance thresholds of both systems.

In the second part of the paper, it has been shown that the MAC scheme of the B-AMC DLL provides predictable medium access latencies, which is an essential feature for safety-related aeronautical communications. The RL resource request process guarantees dedicated and predictable access to all registered aircraft. It has been shown on one representative example scenario that the B-AMC system supports the requirements specified in the FCI evaluation scenarios. In addition, the flexible B-AMC DLL design provides large potential for further performance enhancements. Within the MAC sub-layer provisions have been made to support QoS management, however, the QoS management was neither implemented nor available during the past performance simulation work. Implementing QoS will be a major topic of the future work, considering possible adoption of the existing solutions from other commercial solutions, e.g. P34 or WiMax.

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