BROADBAND VHF AERONAUTICAL COMMUNICATIONS SYSTEM BASED ON MC-CDMA
B-VHF CONSORTIUM

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CONTENTS

VHF SPECTRUM SHORTAGE THREATENS AIR TRANSPORT GROWTH....4
B-VHF AS AN INNOVATIVE APPROACH ..............................................5
KEY PROJECT OBJECTIVES...............................................................6
SYSTEM REQUIREMENTS, FUNCTIONAL SCOPE AND OPERATIONAL CONCEPT.....................................................................................7
VHF SPECTRUM AVAILABILITY AND OVERLAY CONCEPT .................8
DETAILED B-VHF SYSTEM DESIGN.........................................................10
PERFORMANCE SIMULATIONS............................................................12
DEPLOYMENT SCENARIOS .................................................................15
TEST-BED EVALUATION.................................................................17
PROJECT SCIENTIFIC ACHIEVEMENTS.............................................19
POTENTIAL FOR FURTHER IMPROVEMENTS....................................20
DISSEMINATION OF RESULTS AND FEEDBACK..............................20
VHF SPECTRUM SHORTAGE THREATENS AIR TRANSPORT GROWTH

Air transport has been identified as a dominant factor for sustainable economic growth world wide, and A/G communications are extremely critical for achieving an Air Traffic Management (ATM) system that is capable of matching all future air traffic demands.

The Very High Frequency (VHF) COM spectrum (118 – 137 MHz) has been globally allocated for aeronautical safety communications over continental areas. This spectrum is currently organised in voice channels of 25 kHz or 8.33 kHz and one unique voice VHF channel is assigned to each Air Traffic Control (ATC) sector or function.

Several narrowband channels within the VHF COM range have been allocated to the aeronautical data links like ACARS (Aircraft Communications Addressing and Reporting System) or VDL (VHF Digital Link).

VHF communications provide good cost to service figures and will remain very attractive for the aviation community on a mid or long term perspective. However, increasing demand for narrowband communications channels (voice, ACARS and VDL) have led to the congestion of the VHF spectrum in Europe and in some other regions.

Moreover, these systems may not be able to provide the capacity and performance required in the long term. Studies clearly indicate that radical improvements are necessary to be able to cope with the expected air traffic growth in future.

The future communication system - including its VHF part - will have to provide more communications capacity and increased capabilities than the existing one!
B-VHF AS AN INNOVATIVE APPROACH

The B-VHF research project has been co-funded by the European Commission within the Sixth Framework Programme. It has investigated a new approach to overcome the communication bottleneck in the aeronautical VHF range. The focus of the B-VHF project was put on the feasibility analysis of a broadband VHF aeronautical communications system based on the OFDM (Orthogonal Frequency Division Multiplexing) MC-CDMA (Multi-Carrier Code-Division Multiple-Access) technology.

The B-VHF system design covers voice and data link services in a safety-related Air Traffic Services (ATS) and Airline Operational Communications (AOC) environment.

Based on the requirements and accordingly on the high-level system design, an operational concept and a deployment concept have been developed for the B-VHF system. Initially, the B-VHF system should be installed and used in parallel with other systems in the congested VHF COM range. During the transition phase, the B-VHF system would successively replace existing narrowband systems, finally remaining as the only system operating in the VHF COM range.

Both the operational concept and the deployment concept allow the system to be deployed and used in the VHF COM range, but also in other spectrum ranges anticipated for aeronautical communications.

Starting from the high-level system design, simulation scenarios and a simulation framework have been developed, allowing for the verification of project goals via detailed simulations at different layers of the communications protocol stack. The simulation campaign started with separate simulations of the B-VHF physical layer and ended with system-wide simulations. The results have shown that the B-VHF system is capable of operating under different scenarios with that number of users corresponding to the expected future air traffic densities and under changing communications demands while providing higher aggregate channel throughput, broader scope of services and a higher performance level than today’s legacy VHF systems.

The project consortium has presented the benefits of this innovative approach to the aeronautical community via broad dissemination of the project achievements.
KEY PROJECT OBJECTIVES

› **Suitability of multi-carrier technology for aeronautical communications**

The B-VHF project identified and resolved the most significant technological challenges of the MC-CDMA technology when applied to aeronautical communications. A real-time test-bed for the B-VHF forward and reverse link has been implemented to assess the suitability of the proposed multi-carrier technology.

› **Increased communications performance and flexibility**

The B-VHF system has been designed to support within the same VHF spectrum an increased number of users than the currently available legacy systems while providing higher aggregate channel throughput. It supports a mixture of communications services with varying Quality of Service (QoS) expectations and it is easily configurable, following changing user needs in each deployment phase.

› **Increased security**

Laboratory measurements on B-VHF forward- and reverse link test-bed have demonstrated the robustness of the adopted multi-carrier OFDM physical layer to narrowband interference. The system design allows the integration of end-to-end security applications. However, such applications need a mature end-to-end security concept accompanied by a threat analysis and therefore it could not be developed within the B-VHF project.

› **Operational feasibility of deployment concept**

The project produced a set of scenarios for an initial system deployment in the VHF and other ranges, both with voluntary and mandatory equipage, with smooth transition towards the final system deployment. The proposed scenarios are well aligned with operational concepts for the introductory phase and for the time period ten years after an initial introduction.

› **Feasibility of overlay concept in the VHF band**

With an overlay concept, the B-VHF system locally re-uses spectral resources in the VHF COM range allocated to the narrowband systems that continue operating within the broadband B-VHF channel. The project results have proven the feasibility of the B-VHF overlay concept if the two systems remain separated by some protection distance. However, implementing a B-VHF system considerable effort must be spend on reducing side-lobes of the transmitted B-VHF signal and, in particular, on mitigating interference from legacy VHF systems at the B-VHF receiver.
SYSTEM REQUIREMENTS, FUNCTIONAL SCOPE AND OPERATIONAL CONCEPT

The requirements for the B-VHF system have been derived from the EUROCONTROL Operating Concept of the Mobile Aviation Communication Infrastructure Supporting ATM beyond 2015 (MACONDO) and other public strategic ATM documents. Functional and performance requirements of an integrated voice and data link B-VHF system have been taken into account.

The B-VHF functional scope, system design and the operational concept consider specific requirements of ATS and AOC voice and data link services.

The B-VHF system was designed as a cellular terrestrial broadband system using time-division duplex (TDD). The combination of TDD access with the multi-carrier OFDM physical layer provides capacity and robustness combined with operational flexibility that is required for future ATM communications.

The B-VHF communication concept assumes star-topology where aircraft within a certain volume of space, called B-VHF cell, are connected to the controlling Ground Station (GS). Each B-VHF GS provides multiple voice and data communications services to its users by using a dedicated broadband VHF channel. The channel bandwidth is configurable in a flexible way to provide the necessary number of communication channels.

Physical line-of-sight coverage of a B-VHF cell operating in the VHF COM range is independent from the operational service coverage - e.g. voice coverage for a large ATC sector - that is achieved by installing the service at a certain number of B-VHF cells. In contrast to the operational handoff between voice channels that remains human-controlled, the handover between involved B-VHF cells is automatic and fully transparent to the users.

The voice part of an integrated B-VHF system provides a dedicated party-line voice channel to each ATC function and supports a broadcast service as well. Additionally, voice circuits for a selective AOC voice service can be established on demand, upon an explicit air or ground user’s request. When providing voice services, the B-VHF system re-uses the vocoder algorithm that has been adopted for the VHF Digital Link (VDL) Mode 3.

The B-VHF data link sub-system comprises bi-directional acknowledged point-to-point air-ground data link suitable for integration as a sub-network of Aeronautical Telecommunication Network (ATN). Non-ATN point-to-point data link and non-ATN broadcast/multicast data link are supported as well.

B-VHF system design features:
- Cellular terrestrial full-duplex (TDD) system
- Broadband multi-carrier system
- Forward link: MC-CDMA
- Reverse link: OFDMA
- Line-of-sight coverage in VHF range
- Support for legacy and future ATS and AOC voice and data link services

B-VHF system design was based on strategic ATM documents!
VHF SPECTRUM AVAILABILITY AND OVERLAY CONCEPT

Different types of communications systems are currently operated within the VHF COM band (118-137 MHz), like DSB-AM (Dual Side Band Amplitude Modulated) 25 kHz and 8.33 kHz voice systems, ACARS data link, VDL Mode 2 and VDL Mode 4 data links.

The starting hypothesis for the B-VHF overlay concept was that the B-VHF system can locally re-use VHF channels carrying weak signals stemming from distant narrowband transmitters.

It is distinguished between weak (W) and strong (S) interferers depending on whether the received interference power in a given narrowband channel is below or above the specified threshold.

Those narrowband channels, which are only containing weak interferers, may be re-used by the B-VHF system. A group of OFDM carriers of the B-VHF system can be placed over that channels, but the B-VHF system have to cope with the remaining weak interference from narrowband transmitters.

The channels containing strong interferers cannot be re-used as the B-VHF system would jam close narrowband receivers operating in that channel. Finally, a local broadband B-VHF channel can be composed from non-contiguous OFDM carrier groups, providing additional communications capacity without causing interference towards legacy narrowband systems.

The B-VHF project assessed via measurements and simulations the current usage of the VHF COM band spectral resources and the spectrum availability for interference-free operation assuming an overlay concept.
The measurement campaign produced detailed data about instantaneous VHF spectrum occupancy in Europe, comprising several hours of ground measurements at representative ground locations around Heathrow Airport in the UK as well as more than 12 hours of dedicated measurement flights carried out during peak traffic hours at different flight levels in the UK and in Central Europe. The crude data captured with a spectrum analyser at a two sample per second rate have been further processed, analysed and used for B-VHF system design decisions.

In parallel to this measurement campaign, a theoretical interference analysis has been performed using the NAVSIM tool. This investigation was based on the deterministic worst-case users’ topology. Towards the end of the project, supplementary simulations have been performed in order to obtain worst-case spectrum availability at representative airports in Europe.

The results of these activities lead to the conclusion that the overlay concept is feasible, but the local spectrum availability strongly varies within the European airspace.
DETAILED B-VHF SYSTEM DESIGN

The detailed B-VHF system design is based on the previously established system requirements and comprises B-VHF system-specific, user-transparent methods that are required for the system itself to work, including the system initialisation, automated net entry, seamless handover for wide-area coverage voice and data services, as well as internal procedures for service selection and resource allocation. The B-VHF system design supports a broad scope of aeronautical communications services and considers different priorities and quality of service as required for a specific application.

All important features of existing voice and data link systems are re-built within the B-VHF system. As an example, the party-line feature that is today based on direct air-air connectivity has been realised within the B-VHF system via re-transmission of pilot’s voice received via a dedicated ground station (GS) to all other aircraft within the coverage range of this GS (and eventually other involved GSs). Due to the implemented access arbitration feature, the controller’s voice transmission will always interrupt any ongoing re-transmission (the controller has the highest priority).

The B-VHF data sub-system comprises an ATN-compatible air-ground data link, as well as non-ATN point-to-point and broadcast data links in support of extended surveillance and autonomous aircraft operations. Optionally, a non-ATN air-air data link could be provided as well.

Opposite to the voice communications that mainly use permanent physical channels, the B-VHF system allocates resources for a data link only upon explicit user request. This improves the system communications capacity and provides the flexibility required on the transition path after an initial system deployment.

The multi-carrier B-VHF physical layer is based on OFDM. MC-CDMA has been selected as the multiple access scheme for the B-VHF forward link, whilst the reverse link uses OFDMA (Orthogonal Frequency-Division Multiple-Access). Physical OFDM carriers are organised into different types of physical transport channels that can be allocated for different types of communications services.
The B-VHF Data Link Layer (DLL) solution comprises multiple types of logical channels and transport channels. The Media Access Control (MAC) sub-layer maps the system and user data from the transport channels to physical transport channels and finally to appropriate forward- and reverse link time slots within the so called B-VHF super-frame.

The B-VHF system airborne architecture would comprise three B-VHF radio units. Each unit may be dedicated to voice or data link or provide simultaneously voice and data link services.

The concept of the B-VHF airborne architecture avoids the need to substantially change existing avionics. Similarly, as long as only basic voice features are required, no changes to existing Voice Communications Systems (VCS) are needed.

A ground architecture supporting B-VHF may consist of:
- Ground B-VHF radios
- Ground station controller (GSC)
- Ground network interface (GNI)

GNI is an access point for external voice and data systems!
PERFORMANCE SIMULATIONS

The design of the B-VHF physical (PHY) layer has been validated through simulations of the proposed algorithms. Overall system performance in presence of interference from legacy VHF systems towards the B-VHF system has been simulated as well.

Simulation scenarios consider different flight phases with appropriate broadband channel models, e.g. take-off and landing, parking, or en-route flights, taking typical and worst-case interference situations into account. The corresponding interference scenarios – position of strong and weak interferers within the used broadband channel and the signal power statistics - have been retrieved from the measurement flights as well as from the NAVSIM simulation tool.

NAVSIM calculates the worst-case VHF channel occupancy at a certain location, for a certain cell size, during a certain time span. For this purpose, all GS are considered to be active and for each ATC sector one representative interfering aircraft is placed as close as possible to the simulated victim aircraft. Moreover, a duty cycle of 100% for GS and aircraft transmissions is used. With that setting, the worst-case is obtained (lowest number of available VHF channels/ maximum interference).

The interference is modelled according to the results retrieved from the measurement campaign.

Multiple options for interference suppression by spectral shaping in the transmitter have been investigated. The figure below shows the proposed spectrum shaping method (green line) that allows for efficient suppressing the B-VHF signal outside the B-VHF bandwidth and thus reducing the interference caused by the transmitted B-VHF signals on the narrowband legacy systems.
The design of the PHY layer and the overlay concept itself are evaluated by means of software simulations. The performance has been evaluated by means of bit error rate (BER) and frame error rate (FER) in dependence of the total received power for a given interference scenario and noise floor.

A specific synchronisation approach in a high-interference environment has been investigated, taking selected representative broadband VHF channel models into account. For reasons of simplicity perfect synchronization and channel estimation has been assumed when conducting the simulations.

Several options for reducing interference within the B-VHF receiver have been investigated. The figure above depicts the BER performance of the B-VHF receiver for voice transmissions in the forward link en-route interference scenario with two strong and two weak interferers, assuming a total noise power of -110 dBm within one MHz bandwidth. The x-axis represents the total RX power of all used sub-carriers in dBm. The best result was obtained by applying both windowing and leakage compensation to the strong and weak interferers (lower green line). The required RX power required for achieving the target BER = 10^{-3} for voice services could be significantly reduced compared to the reference case without narrowband interference (NBI) mitigation. The overall system performance can be further improved by applying more accurate NBI estimation and/or an improved windowing functions.
The B-VHF data link layer protocol has been designed to provide voice and data services in an aeronautical context, e.g. broadcast, party line and on-demand voice communications, supplemented by the connection-oriented and connectionless data transfer.

Data traffic patterns were defined for three air traffic scenarios and were projected for the years 2015, 2020 and 2025. The BER retrieved from the PHY layer simulations (which depends on the used modulation, coding rate, spreading sequence, etc.) has been converted into the FER and applied to assess the system performance for different transport channels.

Two modulation schemes (QPSK, 64-QAM) have been investigated for the data link. The access delay to the communications channel introduced by the used access algorithm has been considered when simulating the net entry and resource acquisition performance.

As B-VHF party-line voice traffic is not influenced by the data traffic, the end-to-end performance of the voice system has been evaluated in a custom scenario, using QPSK modulation. In order to simulate party line functionality, this special scenario comprises a varying number of aircraft communicating with each other (via relay) and with the GS. Every relayed aircraft transmission consists of two distinct voice messages: one message from the aircraft to ground and another message from the GS to all aircraft. Statistics has been collected for every completed one-way transmission. The simulation results have shown that the B-VHF system is able to support digital voice services with the quality of service as defined in requirements for the voice system.

In the course of the B-VHF project a wide range of simulation settings have been investigated, each setting comprising one B-VHF cell. An appropriate arrival and departure aircraft population with up to 255 registered aircraft per cell has been generated for three air traffic scenarios:

- Parking
- Take-Off and Landing
- En-route

End-to-end simulations of the link establishment time and latency have shown that, when using 64-QAM, capacity requirements and quality of service (QoS) could be met for both voice and data transmissions.
DEPLOYMENT SCENARIOS

Options for the system deployment are dependent on the minimum allowed spacing between the involved systems and should respect frequency planning constraints.

During the elaboration of B-VHF deployment scenarios B-VHF system parameters relevant for the frequency planning (e.g. transmitter power, receiver sensitivity) have been estimated. Assumptions had to be made about the B-VHF radio frequency (RF) front-end performance, as the B-VHF test-bed radio hardware developed in the course of the project might be not representative for the mature B-VHF system. Hence, further work is required towards system standardisation and technical maturity.

Several scenarios have been developed for an initial B-VHF system deployment, transition phase and the full system deployment in the VHF COM range and other spectrum ranges (NAV-band, L-band, C-band) that may become available to new communications systems.

It is expected that an airborne B-VHF radio operating in the VHF range will be developed as an extension of the existing airborne VHF Data Radio (VDR) standard. It has been proposed to limit the maximum allowed total signal power of an airborne B-VHF transmitter to the level used by existing VDR radio (25 W).

B-VHF deployment scenarios consider aircraft equipped with B-VHF radios ("B-VHF aircraft") and aircraft carrying narrowband equipment ("NB aircraft").

In addition to the current

- Narrowband (NB) - airspace

Two other options have been identified:

- B-VHF airspace, where B-VHF equipage is mandatory for all aircraft
- B-VHF-supported airspace with voluntary B-VHF equipage
All VHF scenarios are based on a strict overlay concept, requiring no changes of the legacy systems and assuming an integrated voice/data system. The preferred deployment options are a mandatory introduction in the upper En-route airspace and voluntary equipage in other airspace types. In scenarios with mixed population gateways must be realised within the ground voice system to preserve party-line between the B-VHF voice channel and the corresponding DSB-AM voice channel.

Non-VHF scenarios are based on the usage of dedicated channels (without overlay) and are considering a data-only B-VHF system operating in the L-band, C-band or VHF NAV band. In these scenarios, voice services are provided by the DSB-AM system in the VHF range.

In the early deployment phase the B-VHF system offers basic voice services and an ATN-compatible air-ground data link. Selective voice services, surveillance data link and downlink of aircraft parameters are postponed to the transition/final deployment phases.

Scenarios for an initial B-VHF system deployment have been used as a starting point for describing the transition phase and final system deployment. During the transition, more and more airspace becomes converted to B-VHF operation. At the same time, new services are successively added to the system, including selective voice for AOC usage, downlink of aircraft data and powerful new ATS data link services for trajectory-based ATM. During the final deployment phase, improved spectrum occupancy would allow the deployment of the air-air data link and broadcast surveillance services in addition to the existing services.
TEST-BED EVALUATION

A simplified B-VHF test-bed has been implemented to demonstrate the technical feasibility of a B-VHF transmission chain.

The B-VHF test-bed consists of a B-VHF transmitter and a receiver implemented in digital signal processing (DSP) technology combined with a simple low-power transmitter (TX) and receiver (RX) RF front-end.

On the transmitting side, the baseband signal processing is performed within the DSP platform and the analogue signal is fed to the TX RF front-end input at the intermediate frequency. The TX RF front-end converts the signal into the VHF COM band (118 - 137 MHz).

The RX RF front-end converts the incoming RF signal to the intermediate frequency and forwards it to the receiving DSP board where the A/D conversion, baseband signal processing and evaluation take place.

In laboratory measurements the B-VHF forward link (from GS to aircraft) has been investigated. Three DSB-AM airborne radios and one ground radio have been used as narrowband test equipment. For measurement purposes, the DSB-AM channel under test has been adjusted in such a way that it coincides with the centre frequency of the broadband B-VHF signal.

The interference tests have been performed ignoring the realistic B-VHF super-frame structure (continuous interfering B-VHF signal was used, without any gaps in time).

For demonstration purposes, a B-VHF test-frame has been implemented, comprising 128 OFDM carriers. 112 carriers are effectively used for transmission, while 8 carriers on each side of the transmission spectrum serve as a guard band. Considering a carrier spacing of 2.083 kHz the effective system RF bandwidth is equal to 267 kHz.
The interference measurements have been performed with a B-VHF system transmitting over the reception bandwidth of the DSB-AM receiver, comprising the following scenarios:

- **All OFDM carriers are active - 12 carriers may appear within the reception bandwidth of the DSB-AM receiver.**
- **A variable number of OFDM sub-carriers is cancelled (turned-off) around the carrier of the DSB-AM signal, in order to reduce the interference imposed on the AM signal.**

In the latter case the B-VHF transmitter effectively provides a notch of a certain size within the B-VHF spectrum, but without using spectrum shaping algorithms elaborated during the B-VHF PHY layer investigations. By broadening the notched-out area around the DSB-AM signal it is possible to investigate the interference mechanisms between the two systems.

The impact of a VHF DSB-AM voice communications system upon the B-VHF test-bed and vice versa has been determined by using the following tests:

- **B-VHF power spectrum measurements**
- **B-VHF receiver sensitivity evaluation**
- **Analysis of B-VHF interference imposed on analogue voice DSB-AM receiver**
- **Evaluation of DSB-AM interference on B-VHF victim receiver**

The interference limit for the victim DSB-AM receiver has been determined by the undesired squelch break or by the specified maximum tolerable degradation of a desired DSB-AM signal. The limit for the victim B-VHF receiver was defined by the amount of interference where the BER of uncorrected voice exceeds $10^{-3}$.

From the obtained results, preliminary values were derived for the maximum acceptable received narrowband interference power and the B-VHF receiver sensitivity. In addition, the maximal allowed power of the B-VHF transmitter has been determined that guarantees that the legacy VHF system is not disturbed by the B-VHF system.

The results of the test-bed evaluation have been obtained without interference suppression and narrowband interference mitigation at B-VHF TX and RX, respectively. Once the respective algorithms become integrated in the B-VHF test-bed, significant improvements are expected. Further improvements are anticipated if a professional B-VHF transmitter front-end design, using a D/A converter with more than 14 bits resolution and a more sophisticated B-VHF receiver, which utilises narrowband interference mitigation techniques, would be applied.
PROJECT SCIENTIFIC ACHIEVEMENTS

During the B-VHF project following valuable scientific results have been obtained:

- System requirements were defined
- B-VHF functional scope, architecture and high-level system design were defined
- B-VHF system operational concept was developed
- Ground- and airborne measurements of the VHF spectrum occupancy were conducted
- VHF spectrum occupancy for Europe was modelled and simulated
- Detailed B-VHF system design has been elaborated and verified via separate simulations
- Based on the ground measurements, a narrowband interference simulator for DSB-AM and VDL mode 2 was developed
- Broadband VHF channel model was developed
- B-VHF simulation framework has been developed (lowest two layers of the ISO-OSI model)
- B-VHF system performance simulations were carried-out
- B-VHF deployment scenarios were elaborated
- Test-bed has been implemented and evaluated in laboratory, comprising B-VHF forward and reverse links
POTENTIAL FOR FURTHER IMPROVEMENTS

The simulations conducted within the B-VHF project have shown that a B-VHF system concept - and in particular its overlay-based deployment in the VHF COM band - is feasible. At the same time, it could be confirmed that interference conditions in the VHF band are severe, requiring further improvement/optimisation of proposed B-VHF-specific interference mitigation techniques and their validation with an improved B-VHF system demonstrator.

According to EUROCONTROL and FAA roadmaps, aeronautical data link communications should be preferably realized in the L-band, while voice communications should remain in the VHF band, based on existing narrowband systems.

The results of B-VHF system simulations allow for a conclusion that it may be possible to operate the B-VHF system in the L-band while maintaining the main system characteristics as proposed for the VHF solution. The detailed assessment of the feasibility of the data-only B-VHF system operating in the L-band with a supplementary assessment of necessary modifications of the system design should be investigated in detail in future work.

DISSEMINATION OF RESULTS AND FEEDBACK

The results of the B-VHF activities have been presented at the recent ATC Maastricht exhibitions and at several international conferences in Europe and the USA (for further details, please refer to the project’s web-site at www.b-vhf.org).

In 2004, EUROCONTROL and FAA together launched the Future Communications Study (FCS), aiming to identify the most promising technologies that could cover future aeronautical needs. B-VHF is one of technologies that have been assessed by this study, and it has been ranked by both independent FCS evaluators (NASA/ITT and QinetiQ) amongst the most promising future technologies for aeronautical communications in continental airspaces.

The project has established a close relationship to EUROCONTROL and accordingly the final project achievements have been presented to EUROCONTROL.