B-VHF – AN OVERLAY SYSTEM CONCEPT FOR FUTURE ATC COMMUNICATIONS IN THE VHF BAND

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Abstract

In this paper, the European research project B-VHF[1] is introduced which is funded by the European Commission and has started in January 2004. The main goal of the B-VHF project is to prove that it is feasible to establish a multi-carrier based overlay system for future Air Traffic Control (ATC) communications in the Very High Frequency (VHF) band without causing interference to the legacy VHF systems. Note, this overlay system concept enables in-band transition from the current to a future ATC communications system and, thus, allows future ATC communications to stay in the advantageous and protected VHF band.

The focus in this paper is on the technical approach for realizing the overlay concept. Thus, the technology behind B-VHF will be described in detail and how it is applied for realizing an overlay system in the VHF band.

Introduction

Today, ATC communications is still mainly based on analogue voice transmissions in the VHF band using Double Side-Band (DSB) Amplitude Modulation (AM). This technology has been introduced over 50 years ago and utilizes the available VHF spectrum in a highly inefficient manner. Recently, VHF Digital Link (VDL) Mode 2 deployment started in Europe. VDL Mode 2 is the first digital ATC communications medium and makes available ATC data services.

As the volume of air traffic increases, it is expected that the current narrow-band ATC communications systems will reach their saturation point in Europe around 2015-2020, even assuming full VDL Mode 2 and 8.33 kHz deployment [1].

It proved to be possible to replace a large amount of routine voice communication by data link transmission. As the existing voice based communication system will approach its capacity limit within a few years, it has to be replaced by a system additionally supporting selective and broadcast data messages to increase overall capacity. Besides making available both voice and data services, future ATC communications systems shall fulfill the following expectations:

- Support increasing capacity demand for both voice and data traffic beyond 2020
- Make use of available spectrum in a very efficient way
- Increase the robustness against intentional and unintentional interference
- Improve the communication safety
- Comprise feasible deployment scenario
- Reuse existing technological knowledge

Another desirable feature of future ATC communications systems is operation in the VHF band. The exclusive spectrum assignment for aeronautical communications as well as the advantageous propagation characteristics make the VHF band the first choice for a new system.

Various proposals have been considered for accomplishing the long-term update program for ATC communications in the VHF band. These proposals range from plain splitting of 25 kHz channels with separated data link system (VDL Mode 2) to integrated digital voice and data system concepts (VDL Mode 3). These data link concepts are based on the current frequency raster, use narrow-band techniques, and are not expected to fulfill increasing capacity demands beyond 2020. Moreover, during the transition period these data link concepts require rearrangements of the VHF spectrum and exclusive VHF channel assignments to both the legacy VHF systems and the VHF system to be introduced. Thus, the scarce VHF

[1] B-VHF: Broadband VHF Aeronautical Communications System Based on Multi-Carrier Technology

spectrum resource has to be split in a predefined manner among old and new systems during the transition phase.

The B-VHF project aims at developing a future broadband ATC communications system which is capable to fulfill the above mentioned expectations on a future ATC communications system, like increased capacity, high efficiency, increased robustness, and improved communications system safety. Moreover, it is expected that an in-band transition from the current legacy VHF systems to B-VHF is feasible by designing B-VHF as an overlay system. The enabling technology for this approach is Multi-Carrier (MC) communications. The focus in this paper is on the technical approach for realizing the overlay concept using MC communications.

The paper is organized as follows. First, an overview on the current VHF band situation is given, followed by a detailed description of both the system concept and the technical approach for realizing an overlay system in the VHF band. A short description of the B-VHF project comprising the main goals as well as the current status is given at the end of this paper.

Current VHF Band Situation

The VHF aeronautical communications band spans the frequency range 118-137 MHz and is mainly used for ATC voice communications today. Originally, the VHF band has been divided into 760 channels with 25 kHz channel spacing and DSB-AM has been chosen as analogue communications system still used today.

Since VHF voice channels are already at their capacity limits at least in Europe, 8.33 kHz spacing has been suggested and introduced, recently. This step elevates the current capacity limits a little and pushes the "deadline" for running out of capacity a little into the future. Moreover, in Europe VDL Mode 2 deployment already started and some standard applications which formerly used VHF voice communications are transferred towards digital data exchange. This relieves pilots from work load as well as increases VHF voice communications capacity. However, even a full VDL Mode 2 deployment together with 8.33 kHz spacing will not be able to cope with the aeronautical communications traffic expected in the future [1]. Eurocontrol expects that the capacity limits for ATC communications will be reached around 2015-2020.

Frequency managers work hard in order to extract the best possible spectrum efficiency out of the VHF band and, therefore, the VHF band can be considered as completely occupied with respect to assigned VHF channels. This fact is schematically shown in Figure 1.

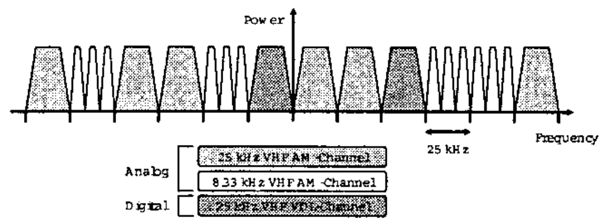

Figure 1. Theoretical VHF Band Occupancy

However, at a certain observation point, e.g. an airborne receiver in an aircraft flying through a certain sector, things might be different in real world. First, some of the assigned VHF channels might be completely unused at certain times. Second, a considerable amount of the assigned VHF channels is assigned to sectors which have large distances to the considered sector and, thus, produce only a small power level at the airborne receiver in the observation point. A more realistic picture of the VHF band occupancy is given in Figure 2 where the different power levels at the observation point are taken into account.

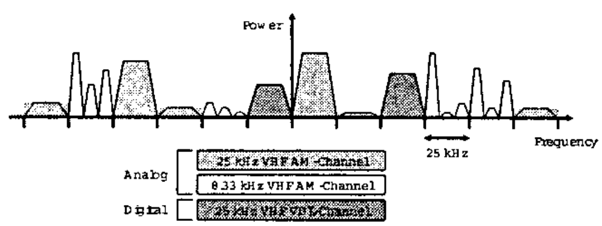

Figure 2. Realistic VHF Band Occupancy

The above considerations show that the received power levels in some VHF channels are small enough to consider these channels as "unused". Using these frequency "gaps" in an adaptive manner enables the introduction of B-VHF for aeronautical ATC communications as an overlay system in the VHF band. Note, B-VHF does not require a continuous part of the VHF spectrum but operates in the VHF band frequency gaps and, therefore, is able to cope with the interference produced by the legacy VHF systems. Moreover, the overlay system itself produces only a small amount of interference power towards the legacy VHF systems. This is especially true since it can be assumed that a modern digital spread-spectrum communications systems as foreseen for B-VHF is more robust against interference as existing analogue or narrowband digital VHF systems. Moreover, the B-VHF system itself produces a lower spectral density and, thus, interference power towards the legacy VHF systems.

System Concept and Technical Approach

B-VHF is a broadband MC communications system proposed for future ATC communications and might be deployed as any other broadband system proposal for future ATC communications, i.e., either by rearranging the VHF spectrum to free a certain continuous part of the VHF band for initial deployment if possible or by introducing the new system initially in another frequency band and, if desired, moving the system later into the VHF band as soon as enough VHF band capacity is available.

Besides these standard procedures, the MC approach of B-VHF additionally offers the possibility of an in-band transition by designing B-VHF as an overlay system. This highly desirable feature makes B-VHF a very attractive candidate for future ATC communications.

Since B-VHF is based on the high-efficient MC technology which is also a promising candidate technology for the next generation mobile communications systems called "Fourth Generation" (4G), B-VHF remains an attractive candidate for future ATC communication even without in-band transition.

In the following, we focus on the MC technology used for B-VHF and show how this technology enables physical layer design necessary to establish an overlay system.

Why MC Approach?

The MC technology is identified as the most promising broadband technology for the next generation mobile communications systems (4G). Currently, several European research projects within the 6th Framework Program of the European Commission are dealing with multi-carrier communications for 4G systems and it is expected that the multi-carrier technology will be standardized as air interface for 4G around 2010-2015.

Considering the current situation in aeronautical communications on the one hand and the development of multi-carrier systems for 4G on the other hand, it becomes obvious that multi-carrier communications is a particularly interesting candidate technology for future aeronautical communications.

First, the multi-carrier technology is highly bandwidth efficient as already proven in the terrestrial broadcast standards DAB (Digital Audio Broadcasting) and DVB-T (Digital Video Broadcasting - Terrestrial) and, therefore, capable to fulfill the increasing capacity demand of future aeronautical communications.

Second, the multi-carrier technology enables an in-band deployment scenario. New broadband aeronautical communications system based on multi-carrier technology can be deployed as an overlay system in the VHF band, co-existing with the legacy VHF systems.

Third, besides already available COTS components for DAB and DVB-T, it is expected that additional new components will soon be developed for 4G systems. Thus, future aeronautical communications systems based on multi-carrier technology can profit from both hardware and software developments made for terrestrial communications.

Taking into account these three aspects, the multi-carrier technology shows some striking advantages over other potential technologies for future aeronautical communications.

The Principle of OFDM

In this section, a brief review of Orthogonal Frequency-Division Multiplexing (OFDM) is provided which is the basic technology almost all MC communications systems are based on. After the OFDM review, two multiple-access techniques which are based on OFDM and considered for B-VHF are described, namely Multi-Carrier Code-Division Multiple-Access (MC-CDMA) and Orthogonal Frequency Division Multiple Access (OFDMA).

The basic idea of OFDM is to convert a serial high-rate data stream into N_c parallel low-rate data sub-streams. Each sub-stream is modulated on one of the N_c sub-carriers. In Figure 3, the basic idea of OFDM is visualized. N_c complex-valued data symbols $\{I(n)\}$, $n = 0,\ldots,N_c - 1$, each having a symbol duration T_s are serial-to-parallel converted. The symbols in each branch are then modulated with a specific sub-carrier frequency f_n, $n = 0,\ldots,N_c - 1$. The sub-carrier frequencies are chosen according to

$$f_n = \frac{n}{T_o},\ n = 0,\ldots,N_c - 1, \qquad (1)$$

in order to guarantee orthogonality among all sub-carrier signals, where T_o is the OFDM symbol duration. The resulting N_c sub-carrier signals are summed up to build the OFDM transmission signal $u(t)$ which is given by

$$u(t) = \frac{1}{N_c}\sum_{n=0}^{N_c-1} I(n)\cdot\exp\left(j2\pi f_n t\right),\ 0 \le t < T_o. \qquad (2)$$

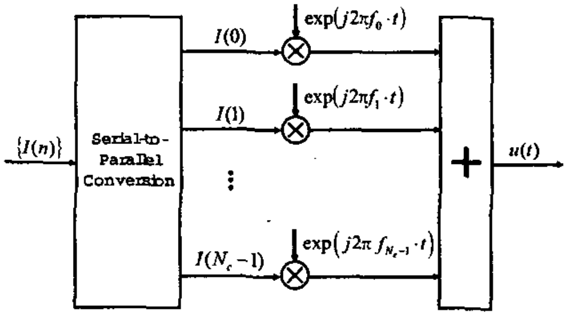

Figure 3. Basic Idea of OFDM

In Figure 4, the orthogonal sub-carriers of the OFDM transmission signal $u(t)$ are shown. The sub-carrier spacing is

$$\Delta f = \frac{1}{T_o} \qquad (3)$$

and the overall bandwidth of the OFDM transmission signal results in

$$B = N_c \cdot \Delta f\,. \qquad (4)$$

The resulting OFDM symbol duration T_o is N_c times larger than the original data symbol duration T_s, i.e.,

$$T_o = N_c \cdot T_s\,, \qquad (5)$$

and consequently the symbol rate on each sub-carriers is reduced by a factor N_c. Thus, OFDM can establish high-rate data communications without suffering from severe Inter-Symbol Interference (ISI) in transmission channels with multipath propagation. Note, other broadband systems have to cope with ISI in multipath channels and, therefore, need complex time-domain equalization. OFDM is even capable to avoid ISI completely by introducing a guard interval at the beginning of each OFDM symbol. This guard interval T_g consists of a cyclic extension of the OFDM symbol and has to be chosen larger than the duration τ_{max} of the channel impulse response

$$T_g \ge \tau_{max}\,. \qquad (6)$$

Taking into account the guard interval the overall OFDM symbol duration T_o' becomes

$$T_o' = T_g + T_o\,. \qquad (7)$$

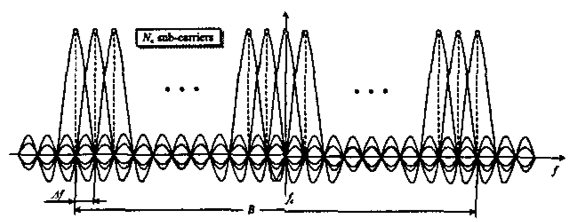

Figure 4. Orthogonal Sub-Carriers of an OFDM Transmission Signal

At a first glance, it seems to be difficult to establish an OFDM based MC transmission system due to the many sub-carriers involved which all have to be exactly tuned to their frequencies f_n in order to guarantee orthogonality. It is easily shown

[2], that OFDM modulation can be established in a very simple and efficient way just by applying the Inverse Discrete Fourier Transformation (IDFT). The set of N_c data symbols $\{I(n)\}$, $n = 0,\ldots,N_c - 1$, are assumed to be complex frequency domain values and the IDFT is applied to them. The resulting time-domain samples are digital-to-analog converted and low-pass filtered resulting in the analogue time-domain OFDM transmission signal $u(t)$. Note, instead of the IDFT the computational efficient Inverse Fast Fourier Transform (IFFT) can be applied for the OFDM modulation.

In Figure 5, the whole transmission chain from transmitter to receiver of a MC transmission system applying OFDM is shown. After analog-to-digital conversion of the received OFDM signal $y(t)$, the resulting samples are serial-to-parallel converted and the guard interval is removed. Then, a Fourier analysis is applied using the DFT or FFT algorithm to retrieve the transmitted data symbols on all sub-carriers. Finally, the data symbols are parallel-to-serial converted again and forwarded to the data sink. For a more detailed description of OFDM, especially comprising channel estimation and equalization or synchronization aspects, please refer to the literature, e.g. [2].

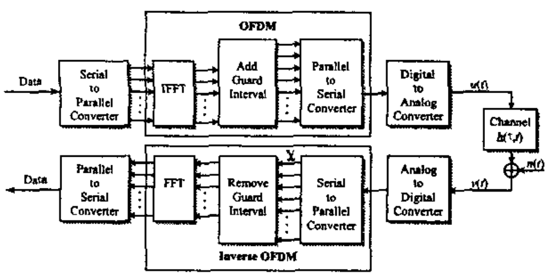

Figure 5. Overall MC Transmission System Applying OFDM

Multi-Carrier Multiple-Access Techniques

There are a lot of possibilities to realize multiple-access techniques based on OFDM. The three standard multiple-access systems – Time-Division Multiple-Access (TDMA), Frequency-Division Multiple-Access, and CDMA – can all be combined with OFDM. Combining TDMA with OFDM results in OFDM-TDMA which is used, for example, in the HIPERLAN/2 standard. Combining FDMA with OFDM gives another multiple-access technique known as OFDM-FDMA or just OFDMA. This technique is not yet used in a standard, but discussed for use in future mobile communications systems, especially in the reverse link, i.e., the link from the mobile to the base station. Due to its promising features in the reverse link, OFDMA is also considered for B-VHF and will be described later. Finally, combining OFDM with CDMA results in MC-CDMA which is the multiple-access technique largely investigated and discussed for 4G mobile radio communications. The B-VHF system proposal is also based on MC-CDMA, at least for the forward link, i.e., the link from the base station to the mobile. In the following, the standard MC-CDMA system is described. Moreover, it is shown how to extend the standard MC-CDMA system to a very flexible multiple-access communications system.

In Figure 6, the standard MC-CDMA transmitter for the forward link is depicted. The data symbols $I^{(k)}$ of each user k, $k = 1,\ldots,K$, within a group of K users are first spread with an user-specific spreading code vector $\mathbf{C}^{(k)}$ of length L. Using orthogonal spreading codes, e.g. Hadamard codes, up to $K = L$ users can be supported simultaneously. After spreading the original data symbol $I^{(k)}$ has been divided into L chips. The chips of all users are summed up and an OFDM modulation is applied to the resulting vector $\mathbf{S}$. The OFDM operation comprises serial-to-parallel conversion, IDFT/IFFT, addition of a guard interval, parallel-to-serial conversion, and digital-to-analog conversion, refer also to Figure 5. Thus, the L chips of one user symbol are distributed on the $N_c = L$ sub-carriers, and the chips of other user symbols are superimposed on the sub-carriers. Note, user signal discrimination is achieved by CDMA with user-specific orthogonal codes. In other words, MC-CDMA is OFDM for the chips of a user data symbol.

Note, the MC-CDMA transmitter of a mobile station is obtained by just considering one user in Figure 6, thus, omitting the other users' signals.

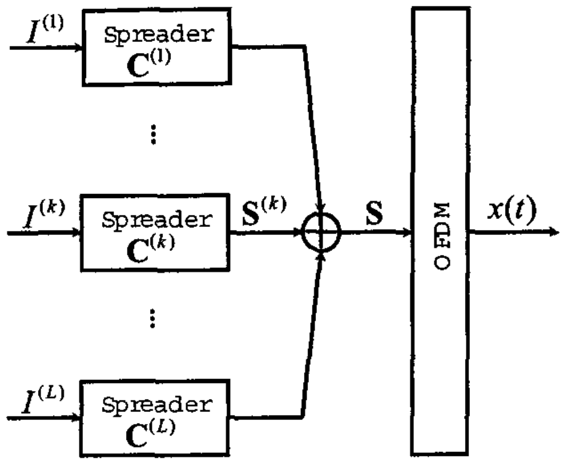

Figure 6. Standard MC-CDMA Transmitter

At the MC-CDMA receiver first the inverse OFDM operation is applied, refer to Figure 5. Then the chips on the different sub-carriers are despread and combined again. Doing this, the original data symbols are retrieved from the received signal. More details on standard MC-CDMA can be found elsewhere, e.g. [2]. Especially, different combining schemes, channel estimation and equalization, and synchronization are discussed there.

In the following, two desirable modifications of the standard MC-CDMA system are described, the so-called *M*- and *Q*-modification. Considering the *M*-modification, each user is allowed to transmit $M > 1$ data symbols simultaneously. This can be accomplished by introducing an additional OFDM component to the standard MC-CDMA system. The chips of the M data symbols are multiplexed on different sub-carriers using OFDM, as shown in Figure 7. All M data symbols $I_m^{(k)}$, $m = 1,\ldots,M$, of user k, $k = 1,\ldots,K$, are transmitted with a separate standard MC-CDMA system. The different MC-CDMA systems are OFDM multiplexed on $N_c = ML$ sub-carriers. Additionally, interleaving is foreseen in order to distribute the chips of one data symbol on sub-carriers as far apart as possible in order to achieve the maximal frequency diversity.

In addition to the *M*-modification, the *Q*-modification can be applied. The basic concept is the same. However, instead of introducing an additional OFDM component, an additional FDMA component is introduced. Thus, instead of increasing the number M of simultaneously transmitted data symbols, the number of simultaneously transmitting users is increased by introducing $Q > 1$ user groups divided by FDMA. Note, each user group can support up to $K = L$ users which are divided by the CDMA component. Figure 8 shows the concept of *M*- and *Q*-modification.

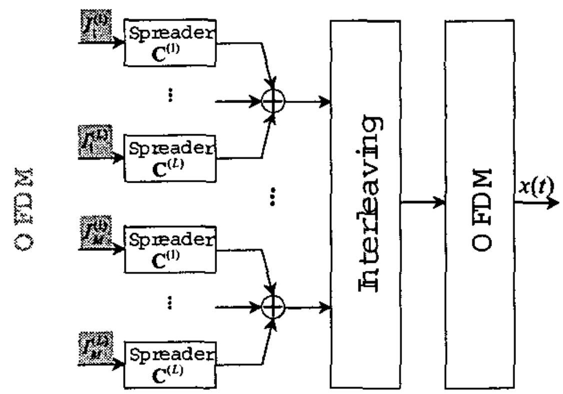

Figure 7. MC-CDMA Transmitter with *M*-Modification

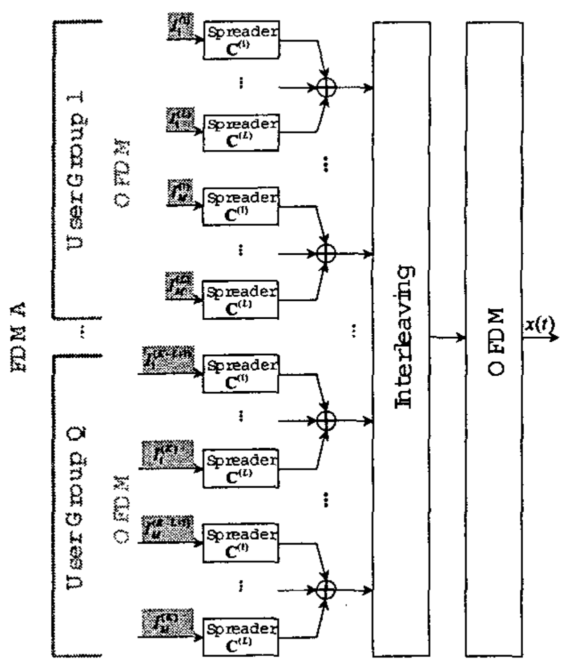

Figure 8. MC-CDMA Transmitter with *M*- and *Q*-Modification

The number of sub-carriers of an MC-CDMA system applying *M*- and *Q*-modification is given by $N_c = MLQ$. From this it can be seen, that MC-CDMA with *M*- and *Q*-modification is a very flexible multiple-access communications system. Assuming a system with a fixed number N_c of sub-carriers, the parameters M, L, Q can be adjusted arbitrarily. The parameter L is the spreading length and is responsible for the achievable frequency diversity. Values in the range $L = 4,\ldots,16$ are a suitable choice depending on the transmission environment. After L is chosen for a certain system design, the product MQ can be split into certain values for M and Q. This can be done adaptively depending on the required transmission data rate and the required user capacity. In the case a large number of users has to be served, Q is chosen large and M is reduced. In times of low user capacity requirements Q can be chosen small, thus, allowing M to be increased and with that the available data rate per user.

The other multiple-access technique considered for B-VHF is OFDMA. Actually, OFDMA can be viewed as a special case of MC-CDMA. Setting $L = 1$ and with that removing the CDMA component changes MC-CDMA with *M*- and *Q*-modification into OFDMA. User discrimination is done only by FDMA, i.e., different users are assigned to different sub-carriers. Note, simultaneous transmission of $M > 1$ data symbols is possible with OFDMA and with that the flexible exchange between data rate and user capacity is maintained. OFDMA is advantageous for application in the reverse link, since channel estimation can be established with a simple pilot-based approach. In Frequency-Division Duplex (FDD) systems, channel estimation for the MC-CDMA reverse link is only possible using blind estimation algorithm. Simple pilot-based channel estimation fails because of the CDMA component. The drawback of OFDMA is that the transmitted data symbols are not spread in frequency and, therefore, are subject to Rayleigh fading in a multipath environment. However, this statement in its strict sense is true only for uncoded transmission. Applying coding and transmitting coded symbols of one codeword simultaneously on different sub-carriers re-establishes frequency diversity at least partly.

The Overlay Concept

Having described OFDM it becomes obvious that the system design of MC communications systems is done in the frequency domain. The sub-carriers are the basic elements and the data symbols to be transmitted are assigned to the sub-carriers according to some mapping rules. Moreover, it becomes possible to skip certain sub-carriers, i.e., to omit them from transmission, by just assigning a zero instead of a complex-valued data symbol value.

B-VHF uses this feature of skipping sub-carriers in order to establish an overlay system in the VHF band. Within the B-VHF bandwidth areas which are already occupied by transmissions of legacy VHF systems are left unused by skipping the respective sub-carriers. The resulting VHF band occupancy reflecting the co-existence of the B-VHF system with the legacy VHF systems is schematically shown in Figure 9.

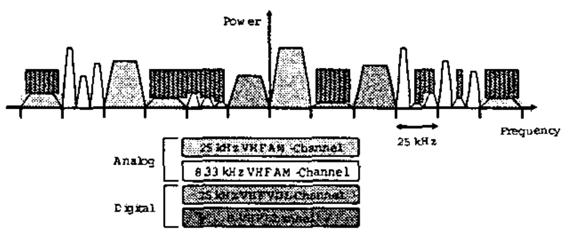

Figure 9. B-VHF Overlay Concept – Using the VHF Band Frequency Gaps

The B-VHF system is based on OFDM, however, there are some design challenges beyond standard OFDM. Avoiding interference from the B-VHF system into the spectrum areas which are not used during B-VHF transmission is one important goal. The sidelobe suppression without any additional countermeasures, i.e., the spectrum resulting by purely omitting some sub-carriers within the B-VHF transmission bandwidth is depicted in Figure 10. Although the sidelobe suppression is already around 20-30 dB, additional countermeasures are developed within the B-VHF project.

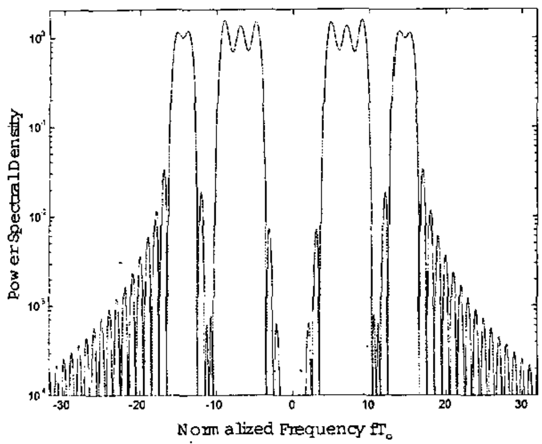

Figure 10. B-VHF Spectrum with Unused Frequency Areas

Another important goal is to suppress or at least mitigate interference which is coming from the legacy VHF systems transmitting near the B-VHF spectrum area or even inside.

Other important areas of B-VHF specific design comprise time and frequency synchronization, channel estimation, and the design of a highly flexible and adaptable OFDM frame structure in order to adjust the B-VHF transmission signal to the actual available spectrum.

The B-VHF Project

The B-VHF project is a European research project within the 6th Framework Program funded by the European Commission. It started on January, 1st this year and will continue until mid 2006. In this section a short overview on the main project goals as well as the current status is provided.

Main Goals

The main goals of the B-VHF project are specified as follows:

- Development of an operational concept for B-VHF and a suitable deployment scenario
- Assessment of the available VHF spectrum for the overlay approach through both measurements and theoretical analysis of the VHF band occupancy
- Design of an MC based overlay system concept and software implementation of physical layer, data link layer, and upper protocol layers
- Assessment of the B-VHF design by simulations
- Development of a first B-VHF testbed and laboratory interference tests with legacy VHF systems

Current Status

Applications communications requirements as well as the high level system design have already been established for B-VHF. Moreover, the design of the physical layer as well as the channel and interference modeling task have started.

Currently, the VHF band occupancy measurements are performed using a specially adopted spectrum analyzer which is capable of measuring the whole VHF spectrum from 118-137 MHz continuously and record the measurement results with a rate of 2 measurements per second. Both ground measurements in the vicinity of a large airport and measurements on three different flight levels are performed. The results of these measurements will be cross-checked with the theoretical analysis obtained using the simulation tool NAVSIM provided by University of Salzburg. The expected result of the measurements and the theoretical analysis is an estimate on the actual VHF band occupancy. This result will be used for the further physical layer design.

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