Technical feasibility study and field trial concept for DRM-based digital radio in the VHF-FM radio band

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ABSTRACT

This paper discusses the key outcomes of a technical feasibility study on a frequency grid-conforming DRM-based transmission scheme in the VHF-FM radio band, focussing on transmission and radio planning aspects. A field trial concept for a complete prototype transmission chain to complement the theoretical results by measurements is presented.

KEYWORDS

Digital Radio Broadcasting, Digital Radio Mondiale, digital switch-over in the VHF-FM radio band.

INTRODUCTION

All over the world, ambitious efforts are being made to introduce digital radio broadcasting in the VHF-FM radio band. In the USA, 'HD radio' [1] has already been introduced. From a global perspective, at present, the DRM consortium enhances the existing DRM standard for the use in the classical VHF-FM radio band [2].

In Germany, digitization of the VHF-FM radio band (87.5 – 108 MHz) is both a technical and a political objective. The 'starting scenario 2000' of the 'Initiative Digitaler Rundfunk' (IDR) [3] challenges the take-over from analogue FM to DAB up to 2015. Meanwhile, it is commonly agreed that this goal cannot be reached [4]. However, a good chance for changing over to digital transmission schemes exists if (instead of DAB) a frequency grid-conforming system is introduced. Doing so allows for subsequent 'digitization' of single VHF-FM frequencies during a transition period, an approach which has proved to be successful when launching the DVB-T starting spots. This paper describes such an approach based on an 'upgraded' version of DRM. The authors intend to contribute to the ongoing work of determining the technical advantages and disadvantages of possible candidate digital transmission schemes currently under investigation for the VHF-FM radio band.

This article is organized as follows: The section TECHNICAL FEASIBILITY STUDY summarizes the approach chosen for the technical feasibility study and presents key outcomes. The Section FIELD TRIAL CONCEPT describes the ongoing work at the time of submitting the camera-ready version of this paper. The focus lies on the software and hardware concept adopted in order to translate the theoretical results into action. The section FUTURE WORK gives a brief outlook of work the authors intend to proceed with once the field trial setup is complete. Finally, the section CONCLUSIONS gives a brief summary.

TECHNICAL FEASIBILITY STUDY

Set Points

In 2005, the University of Applied Sciences in Kaiserslautern ('FH Kaiserslautern') made an investigation to find out if a grid-conforming digital transmission scheme succeeding the VHF-FM radio could be defined in such a way that the demands on modern radio are satisfied [5],[6]. The state-of-the-art transmission principles of the DRM standard were defined as starting point. Further key requirements for the system were defined as follows:

- Both coverage and structures of the existing VHF-FM systems should be mapped onto the new system, fully accounting for speeds up to 300 km/h, for the characteristics of portable receivers and for full indoor reception.
- In order to enhance audio quality, at least one program in a CD-like quality including program associated data (PAD) should be transmitted.
- From a radio planning perspective, the system should be well suited for single frequency networks (SFN).
- Switching over to digital transmission on a single VHF-FM frequency should be possible without causing distortion to the remaining FM networks.

Table 1 summarizes the overall technical set points for the investigation.

Table 1. Technical set points for the investigation

System bandwidth	100 kHz
Modulation scheme	OFDM
Subcarrier modulation scheme	4-, 16- and 64-QAM
Coded bit error rate	10^{-4}
Channel model	'Urban Area'
Channel coding scheme	Convolutional, $R = 0.5$
SFN TX-distances	60 km

Calculation of OFDM parameters

The minimum required C/N ratio for demodulation was estimated using the analytical approach described in [7] for urban area environment and a code rate of R equal to 0.5. Results obtained were increased by a rather conservative figure of 3 dB to account for further losses due to e.g. non-perfect channel estimation. **Table 2** shows the findings for the minimum required C/N ratio for demodulation. Starting with the figures given in Table 2 and assuming further characteristic receiver and environment parameters, e.g. sensitivity or speed-dependent intersymbol-interference due to Doppler shift, the minimum required received power at the receiver antenna listed in **Table 3** was calculated for three different receiving conditions, namely stationary, portable and mobile reception. Note that in the case of 64-QAM, the intersymbol-interference for 300 km/h is so dominant that the resulting data rate gets too small. In this case, the speed requirement is reduced to 200 km/h in order to guarantee both a sufficiently high net data rate and the required SFN capability. Setting out from the results shown in Table 3, characteristic parameter settings for different modulation schemes were determined, cf. **Table 4**. Based on Table 4, both the achievable gross and the net data rates were identified. Net data rates less the assumed data rates necessary for the provision of system information finally yield the audio data rates, cf. **Table 5**. Inspecting Table 5 reveals that, assuming MPEG 4-AAC coding, in any case, a high quality stereo program including PAD can be provided.

Table 2. Minimum required C/N for demodulation

4-QAM	16-QAM	64-QAM
15 dB	25 dB	33 dB

Table 3. Minimum required received power

	Receiving condition		
	stationary	portable	mobile
4-QAM	-102 dBmW	-102 dBmW	-99 dBmW@300 km/h
16-QAM	-92 dBmW	-92 dBmW	-84 dBmW@300 km/h
64-QAM	-84 dBmW	-84 dBmW	-80 dBmW@200 km/h

Table 4. Settings for different modulation schemes

	Modulation scheme		
	4-QAM	16-QAM	64-QAM
Bandwidth	100 kHz		
Subcarrier spacing	375 Hz	750 Hz	1500 Hz
# of subcarriers	266	132	66
Max. speed	300 km/h		200 km/h
QAM-symbol duration	2.667 ms	1.333 ms	0.667 ms
Guard interval	166.667 µs		
Duration of OFDM symbol	2.833 ms	1.5 ms	0.833 ms
# of pilot subcarriers per OFDM symbol	11		

Table 5. Data rates for different modulation schemes

	Modulation scheme		
	4-QAM	16-QAM	64-QAM
Gross data rate	187.7 kbit/s	352.0 kbit/s	475.2 kbit/s
Net data rate	93.5 kbit/s	175.5 kbit/s	237.5 kbit/s
Audio data rate	79.5 kbit/s	149.1 kbit/s	201.8 kbit/s

Minimum required field strength for radio network planning

Up to now, the focus lay on the basic transmission parameters. Now the aspect of radio network planning, i.e. the estimation of the parameter settings relevant for planning the radio transmission network, shall be highlighted.

A classical approach in radio broadcasting network planning is based on the so called ‘planning field strength’, a ‘virtual’ field strength which actually differs from the field strength derivable from the values shown in Table 3. This difference results from additional margins due to, e.g., assumed antenna type, height and orientation, propagation model, coverage probabilities related to both receiver location and time. The ITU-R approach [8] is adopted for both planning and compatibility considerations. This model defines additional margins for the link budget calculation to relate the values given in Table 3 with the planning field strength.

For planning purposes, the following typical receiving situations (cf. Table 3) were identified, leading to the results given in **Table 6**[1].

- Stationary: Reception with a roof-top antenna, comparable to classical FM planning,
- Portable outdoors: Reception with portable battery-powered radios out of doors, typically pedestrian,
- Portable indoors: Reception with stationary power outlet operated radios in house,
- Mobile: Car reception, comparable to DAB planning.

Table 6. Planning field strength

	Receiving scenario			
	stationary	Portable outdoors	portable indoors	mobile @300 km/h
4-QAM	10 dBµV/m	35 dBµV/m	42 dBµV/m	41 dBµV/m
16-QAM	20 dBµV/m	45 dBµV/m	52 dBµV/m	57 dBµV/m
64-QAM	28 dBµV/m	53 dBµV/m	60 dBµV/m	61 dBµV/m
FM Stereo	54 dBµV/m	*n.d.*	*n.d.*	*n.d.*
T-DAB	35 dBµV/m	56 dBµV/m	59 dBµV/m	60 dBµV/m.

Comparing the values for stationary reception reveals that 4-QAM and 16-QAM get by with substantially less field strength as the remaining schemes. Furthermore, 64-QAM and T-DAB seem to be equivalent with respect to field strength needed. The conclusion to be drawn is that a digital transmission scheme can maintain the same coverage with less transmission power, or, vice versa, coverage is increased while keeping transmission power constant.

Intersystem compatibility

In order to protect the existing analogue VHF-FM networks, the OFDM signal needs to be filtered so that it fits into the ITU spectrum mask defined for FM [10]. **Figure 1** shows the spectrum masks for FM as well as those assumed for the different-QAM schemes under investigation. Based on the spectrum masks defined in Figure 1, the protection ratios for different interference scenarios were calculated, namely FM → FM (FM interferes FM),

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[1] For DAB and VHF-FM see e.g. [9], [10]

FM → 16-QAM, 16-QAM → FM, and, 16-QAM → 16-QAM, cf. **Table 7**.

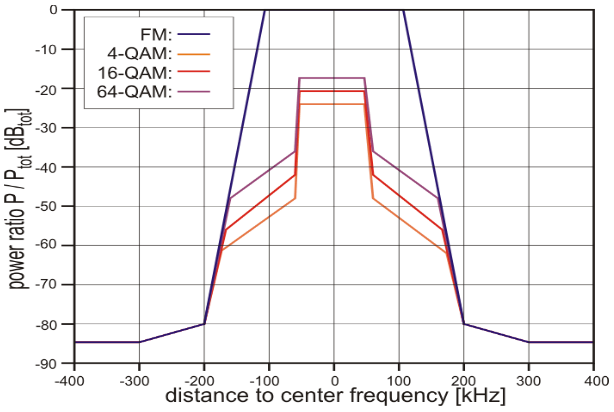

FIGURE 1. SPECTRUM MASKS

Table 7: Protection ratios FM (Stereo) - 16-QAM[2]

Channel separation	FM → FM	FM → 16-QAM	16-QAM → FM	16-QAM → 16-QAM
Cochannel	45 dB	25 dB	30 dB	25 dB
± 100 kHz	33 dB	25 dB	30 dB	25 dB
± 200 kHz	7 dB	-8 dB	13.5 dB	8.5 dB
± 300 kHz	-7 dB	<-40 dB	-9.5 dB	-14.5 dB
± 400 kHz	-20 dB	<-40 dB	-29 dB	-34 dB

The results presented in Table 7 suggest that a digital transmission scheme introduces less interference into an existing analogue FM coverage as compared to the reverse situation. Therefore, a single frequency could easily be switched from analogue to digital transmission, except for the ±200 kHz vicinity: Here, to get interference under control, further lowering the spectrum mask by filtering and/or reducing transmit power are obvious measures to take. Looking into the last column of Table 7 indicates that radio network planning becomes easier in a pure digital environment.

SFN capability

Using channel assignment algorithms, the number of channels to achieve federal state wide coverage lies between 5 and 6, whereas, for regional and local coverages, 10 to 15 channels are necessary for SFN networks. Considering the existing VHF-FM coverage situation, a rough estimate proposes that 24 to 30 channels are receivable in an arbitrary location. Thus, the existing program variety can be not only guaranteed but enlarged, and coverage lacks can easily be filled by repeaters.

FIELD TRIAL CONCEPT

Objective

The university location Kaiserslautern disposes of a nearly complete transmission chain for DRM. The transmitter core is made up of 'Spark' [11], developed at the FH Kaiserslautern. Spark is an open source real-time software DRM transmitter implementing the complete DRM standard [12] including the MDI-interface [13],[14]. Likewise, the nucleus of the receiver consists of 'Diorama' [15], a complete open-source real-time software DRM receiver, which has been developed at the Technical University (TU) of Kaiserslautern.

Based on the findings reported in the first section of this paper a field trial system for the VHF-FM was set up, aiming at

- adapting the DRM standard with a minimal set of modifications,
- setting up a simple, but complete prototype transmission chain, consisting of transmitter and receiver based on 'upgraded' versions of Spark and Diorama,
- conducting field measurements focussing on aspects of radio network planning and coexistence scenarios, e.g. actual FM systems,
- contributing to the ongoing DRM standardization process by providing all results to the DRM consortium.

Modifications on DRM

By the turn of 2005/2006, FH and TU Kaiserslautern discussed and adopted a set of modifications on DRM as a basis for the prototype field test environment. These modifications comprise inter alia the redefinition of

- physical OFDM parameters,
- transmission superframe (TSF) parameters, i.e. its structure, carrier positions and pilots (time, frequency and gain references),
- channel parameters, i.e. the MSC (cell interleaving, multiplexing, audio coding), SDC (stream description, data entities) and FAC (channel and service parameters).

An example of the chosen parameter settings for a 16-QAM modulation scheme and 15 AAC frames per transmission frame (TF) is given in **Table 8**.

Transmitter

Figure 2 reflects the block diagram of the chosen transmitter concept. For a better legibility, all blocks are numbered in parenthesis. First, the input signal **(1)** - typically an analogue audio source - is sampled using a conventional high quality sound card **(2)**. The digitized audio stream is fed into the 'upgraded' version of Spark **(3)**, whose main extensions can be outlined as follows:

- All modifications according to the previous section are incorporated.
- Resampling of the I/Q components to an arbitrary sample rate using polyphase filter techniques with high quality sin(*x*)/*x*-interpolation [16]. The aim is to decouple the DAC rate from the timebase predefined by the physical OFDM parameters, cf. Table 8.
- Due to the higher bandwidth of the OFDM baseband signal, DAC using conventional sound cards is no longer suitable. Instead, a fast data acquisition card **(4)**

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[2] The corresponding figures for 4 QAM and 64 QAM differ slightly

(PCI-6125, [17]) is used to output the I/Q components of the analytical OFDM modulated signal via two analogue outputs at an arbitrary ‘DC frequency’, denoted as f_{DC} in the sequel, ranging from 0 to 1 MHz.

Table 8. Example parameter settings 16-QAM, 15 AACs / TF

Timebase	
Input sample rate	48 kHz
# samples / AAC frame	960
→ Duration of AAC frame	20 ms
# AAC frames / AAC superframe	10
→ Duration of transmission frame	200 ms
OFDM & TSF parameters	
Duration of OFDM symbol	4/3 ms
→ # OFDM symbols / TSF	150
# cells / symbol	111
Lower carrier index	-55
→ Upper carrier index	55
→ Carrier spacing	6/7 kHz
→ Unguarded OFDM signal bandwidth	95.142 kHz
Duration of guard interval	1/6 ms
→ Duration of unguarded OFDM Symbol	7/6 ms
# transmission frames / TSF	2
→ Duration of TSF	400 ms
→ # OFDM symbols / TSF	300
DC carries data	No
Pilot scattering	
Pilot periodicity in frequency domain	10
Pilot periodicity in time domain	10
Pilot DC carrier offset	1
→ Pilot cells / TF	606
→ # free cells / TF	15894
→ # free cells / TSF	31788
SDC configuration	
# OFDM symbols / SDC	4
→ # cells / SDC	419
SDC code rate	0.5
SDC bits / cell	4
→ # SDC bytes	104.75
FAC configuration	
# cells / FAC	65
FAC code rate	0.5
FAC bits / cell	4
→ # FAC bits	130
MSC configuration	
→ # cells/MSC / TSF	31239
MSC code rate	0.5
MSC bits / cell	4
→ # MSC bytes / TSF	7809.75
→ MSC net data rate	156.195 kbit/s

The functionalities of blocks (2), (3) and (4) are associated with a standard PC. As an example, **Figure 3** shows the measured power spectral density of the I component at the output of the block (4) for f_{DC} = 192 kHz. From figure 3, the positions of the frequency references, located at 198, 210 and 216 kHz, can be identified as well as the fact that the DC carries no data.

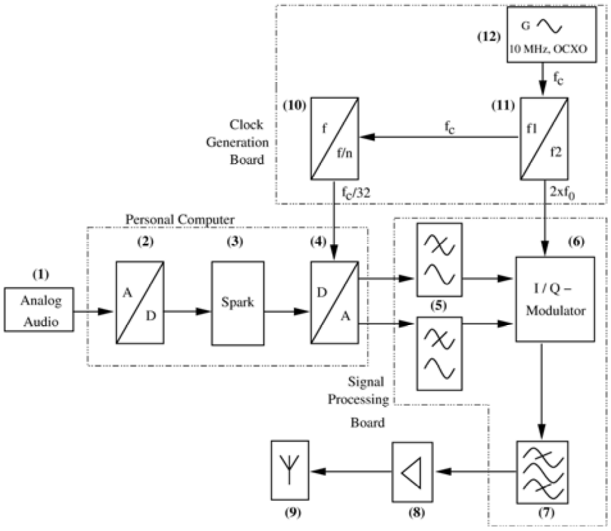

Figure 2. Transmitter block diagram

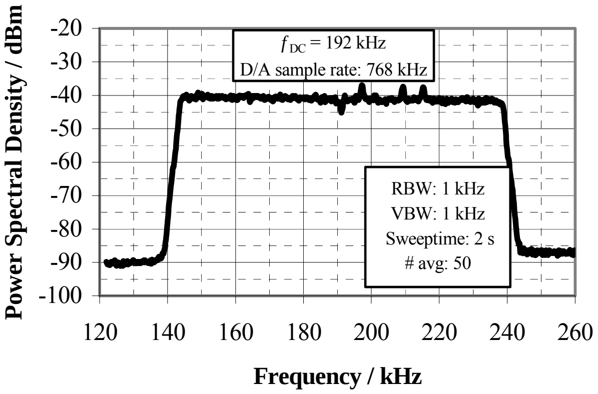

Figure 3: Measured Power spectral density at the output of Block (4)

Next, the analogue complex baseband signal needs to be modulated onto the desired RF carrier frequency f_0. Prior to this process, the aliasing components of the I/Q signals are suppressed by low noise continuous time filters **(5)** (MAX274 [18]). In order to minimise the effect of signal distortions due to frequency selective group delays in the pass-band, these filters show Bessel characteristics of 8th order. **Figure 4** shows the measured magnitude of the frequency response as well as the phase from 0 to 100 kHz. The curves slightly differ from theory mainly due to the quantisation of the calculated values of resistors and capacities to those values available from the resistance and capacitor series. The design focussed on a linear phase in the pass-band, accepting a slight bulge in the attenuation characteristics.

For modulation onto the RF carrier, the monolithic integrated quadrature modulator RF2713 [19] **(6)** is used. The complex baseband signal is converted directly, i.e. without using IFs, thus avoiding the necessity of image rejection and related filter problems. The most critical parameters of the modulator in terms of distortion of the OFDM signal are I/Q amplitude balance, quadrature phase error, carrier and sideband suppression, and, dynamic range (1 dB compression point).

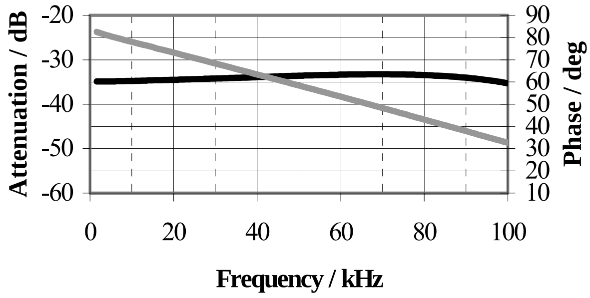

Figure 4. Measured magnitude (solid line) and phase (grey line) of the frequency response (block (5))

Finally, the RF signal needs to be amplified and transmitted. To this extend, first, band-pass filtering **(7)** is applied to the RF signal in order to filter out the spectral replica at frequencies of $\pm n \cdot f_0$, $n \neq \pm 1$. A simple classical passive LC-filter tuned to f_0 is used to this extent. The Q-factor of the filter is not yet defined. The RF signal is then fed to the amplifier **(8)**. The most crucial issue related to the amplifier in terms of distortion of the OFDM signal is, again, linearity. Parameters to look at are e.g. the 1 dB compression point and the lower end of the dynamic range. A decision which amplifier to use has not yet been made, but the LZY-1 [20] is short-listed. As a last step, the signal is transmitted via the antenna **(9)**. A typical VHF-FM antenna will be used.

Both the local oscillator signal for the modulator device as well as the sample rate for DAC are derived from a high precision 10 MHz OCXO **(12)** exhibiting a single side-band phase noise less than -110 dBc at 10 kHz offset from 10 MHz. The OCXO's output serves as input to the ICS525 **(11)** which generates a highly accurate clock frequency of $2 \cdot f_0$, the input frequency needed by the modulator device comprising an integrated quadrature frequency divider. The reference output of the ICS525 converts the OCXO signal into a square oscillation and, thus, serves as input to the ICS524 [21], a clock divider **(10)**, whose output is used to trigger the DAC of the I/Q-components.

RECEIVER

The receiver concept includes an appropriate RF front-end resulting in analog-to-digital converted I/Q-components as well as a software-based receiver using a PC audio card for sound output. As a basis for the software receiver Diorama is used. Diorama includes signal processing for acquisition and tracking of time and frequency, equalization, channel and audio decoding as depicted in **Figure 5** [15], [22]. Although the basic methods are well known for OFDM receivers, see e.g. [23], [24], some specific approaches enhancing the receiver performance will briefly be sketched.

For channel estimation and equalization a two dimensional Wiener filter was implemented. The coefficients are precomputed utilizing robust assumptions on channel and noise behavior. Time synchronization for guard interval removal and sample rate adjustment is based on the estimated channel impulse response. Since the clock timing of a PC sound card DAC and ADC usually cannot be controlled, Diorama has to synchronize the incoming OFDM signal and the decoded digital audio signal. To avoid an overrun or underrun of the audio playing buffer, which is clocked by the ADC/DAC hardware, the decoded audio samples also have to pass a resampling stage before analogue audio is generated.

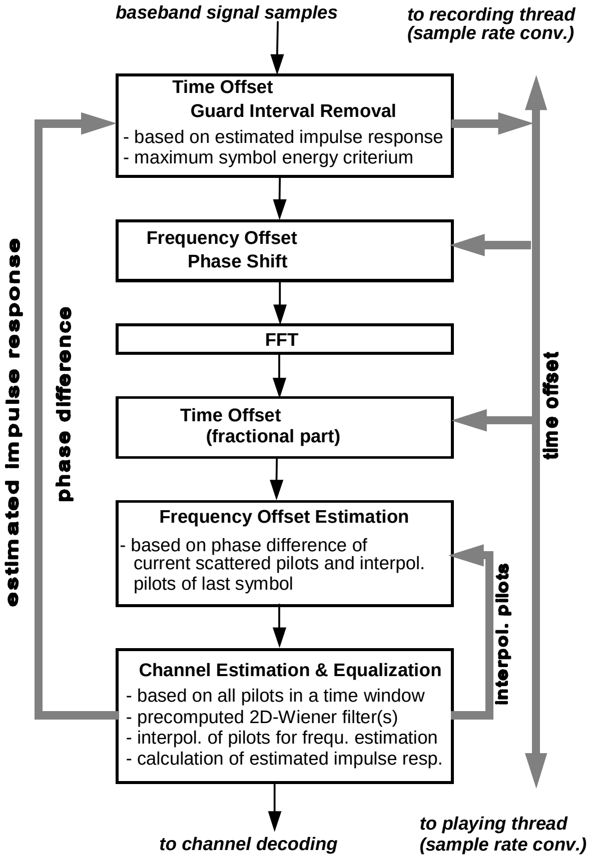

Figure 5. Diorama signal processing

To recover the transmitted data bit streams, the punctured convolutional codes and multilevel coding (MLC) have to be decoded by successive Multi Stage Decoding (MSD). Since the constituent codes are not approaching the channel capacity, Diorama achieves a further decoding gain by iterative decoding of the levels. To additionally improve decoding performance, Diorama estimates the noise variance of the individual carriers using the output of the channel decoders.

From a software point of view, the flexible concept of Diorama makes it possible to adapt the receiver to various system parameters, e.g., to those given in Table 8. Currently, Diorama allows for real-time reception of standard DRM on a 800 MHz PC using MATLAB and C-modules. However, CPU performance limitations of current PCs require some further modifications to allow a DRM receiver, which is upgraded to the system given in Table 8, to play in real-time. Besides substituting time consuming MATLAB modules, current and further projects investigate the potential of multi-core processors. Also, the DSP implementation of Diorama based on Analog Devices' 'Blackfin' is an ongoing work.

Current projects also include the implementation of an RF front-end corresponding to the concept depicted in Figure 2, which will be connected to the PC or DSP via a USB 2.0 interface. The intention is to use the same components as on the transmitters side. However, is has to be checked whether, e.g. the phase noise of the clock rate multiplier ICS525 is low enough for this OFDM setup. Otherwise a direct digital synthesis (DDS) approach could be applied instead.

FUTURE WORK

Based on the concept described in the previous section, a field trial should be started in Kaiserslautern in 2007. An RF frequency of 87.6 MHz, which is coordinated for transmitter powers up to 100 W, will probably be used. The concrete transmitter site location has not been decided on yet.

The ultimate goals are to find out the real and subjective

- differences between digital reception in terms of audio quality and coverage probabilities, cf. the scenarios defined in Table 3 and 4, respectively,
- mutual interference between FM and the OFDM-based approach, a very critical item.

The aspect of mutual interference deserves careful studies since user acceptance of a new transmission scheme depends on the distortion of classical FM reception during the transition period. Since CPM-like transmission schemes are susceptible to introduce less mutual interference, cf. e.g. [25], the extension of both transmitter and receiver to CPM-like modulation schemes is an issue.

Finally, as a terrain of work being identified, the implementation and testing of different receiver concepts, notably in combination with CPM-like transmission schemes, can be listed. In CPM-like schemes, especially the receiver algorithms to be used are far more complex. In this context, SFN capability of CPM-like transmission schemes is an open issue, which needs to be answered.

CONCLUSION

The results presented in this paper clearly indicate that it is possible to design a grid-conforming OFDM-based digital transmission scheme in the VHF-FM band, which excellently fulfils the requirements formulated in Table 1 and allows for smooth transition to digital SFN radio networks. A concept for a complete prototype field trial set up is presented in order to validate theoretical results.

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