Terrestrial DVB (DVB-T): A Broadcast Technology for Stationary Portable and Mobile Use

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Invited Paper

Digital video broadcasting—terrestrial (DVB-T) is the name of the terrestrial transmission system which was developed by the DVB Project. DVB-T is in operation in many countries around the world. This paper analyzes the features of the system. It describes its capabilities with a special emphasis on mobile reception and looks at the introduction of DVB-T in Germany using the launch of DVB-T in this country as a case study. In order to analyze how an MPEG transport stream at the input of a DVB-T modulator is turned into a DVB-T signal, we consider the channel coding and modulation used. Then we look at various aspects of the system performance. The next section deals with mobile reception. Network planning issues, antenna diversity concepts for mobile receivers, and handover procedures will be considered. Finally, the introduction of DVB-T in Germany is presented as a case study. In contrast to various other countries Germany decided to offer DVB-T as a means of providing the "anywhere TV" experience. This implies that DVB-T signals can be received with mobile and portable receivers. In regions with DVB-T coverage analogue terrestrial TV services were discontinued just a few months after the launch of DVB-T.

Keywords*—*Antenna diversity, anywhere TV, broadcast technology, coded orthogonal frequency division multiplexing (COFDM), DVB-T, handover, mobile reception, MRC, network planning, terrestrial TV.

I. Introduction

The commercial requirements for the development of a digital video broadcasting (DVB) system for terrestrial broadcasting date back to early 1994. The main objective at that time was to support the stationary reception of terrestrial signals by means of rooftop antennas. Portable reception was declared as desirable but was not made mandatory, mobile reception was not in the scope of the commercial requirements at all. DVB-T was to have a maximum level of commonality with DVB-S and DVB-C. Consumer-type receivers were to become available from 1997 at reasonable prices. The support of country-wide single-frequency networks (SFNs) was made a requirement. This type of network consists of neighboring transmitters which are in synchronism with each other, operate on the same frequency and transmit identical data streams.

Long discussions about whether to choose a specification with low complexity in order to fulfill the requirements regarding cost and date of first availability of receivers or whether to decide for a solution with higher complexity better meeting the requirements for frequency-efficient SFNs resulted in a DVB-T standard [1] which provides several options. It can therefore be adapted to various modes of network planning.

Trials—among others those that started in the northern part of Germany as early as 1997—demonstrated that the flexibility of the DVB-T system supports networks covering not only stationary receivers connected to rooftop aerials but also portable receivers indoor and mobile receivers in cars and busses [2]. The findings of these trials initiated the development of a plethora of different DVB-T receivers. Such devices are now available as integrated digital TV (IDTV) receivers, set-top boxes, in-car-modules, USB sticks, PC cards, etc.

II. Transport Stream (TS) Processing

The base band signal that is transmitted is a MPEG-2 TS as defined in [3]. The TS is a continuous sequence of TS packets. Each packet has a length of 188 B. The first 4 B contain the header of the TS packet; the following 184 B are used for the payload. The most important components of the header are the synchronization (sync) byte and the packet ID (PID).

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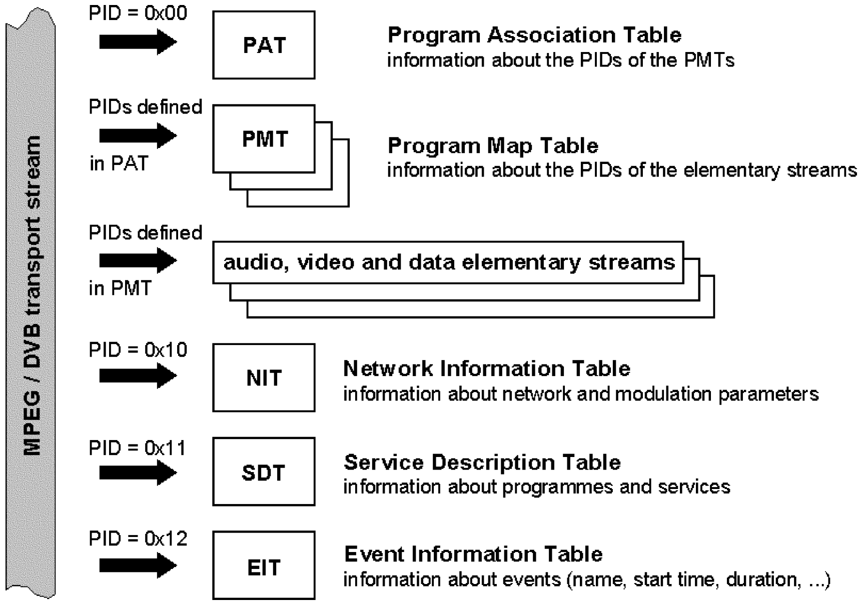

Fig. 1. Access to the components of the DVB TS.

Program-specific information (PSI) as defined by MPEG [3] is used to access the various components constituting the payload of the TS. The PID of the program association table (PAT) is zero (Fig. 1). Thus, the PAT can be directly extracted from the TS and can then be decoded. The PAT informs about the PID values that are used for the program map tables (PMTs). Equipped with this information the receiver can read the PMTs. They contain a list of PID values of the corresponding elementary streams of each service—identified by the program number. One PMT may be used for all services but the data for the different services may also be spread over several individual PMTs.

The elementary streams identified by their PIDs may be video or audio streams but can also carry data like teletext, subtitling, IP packets, or carrousel-based services [4]. The transport mechanism is based on either packetized elementary streams (PESs) or tables [3] that are mapped into the TS packets.

In order to facilitate comfortable access to the services by the users DVB has defined service information (SI) [5] consisting of tables described in the following. The network information table (NIT) describes the modulation parameters of the TSs that are carried over the network. The table can also be used for the transmission of information about alternative frequencies. The NIT is therefore very important for the handover procedures in a mobile environment that will be introduced later. The service description table (SDT) mainly translates program numbers into service names. Further information about the services like language or video aspect ratio can be provided. Another important SI table is the event information table (EIT). Nearly all information offered by a printed program guide can be offered via the EIT in an electronic way. Event name, event start time, event duration, content classification, and different kinds of descriptions are just the main components of the EIT. The data is very useful for implementing an electronic program guide (EPG).

III. Channel Coding and Modulation

Before the base band signal can be transmitted, it has to undergo channel coding and modulation. A forward error correction (FEC) is required which enables the receiver to correct errors that have occurred as a result of noise and other disturbances in the transmission path. Furthermore, a synchronization method has to be provided. The complete block diagram for DVB-T encoding (Fig. 2) can be divided into three parts [6].

The first three blocks are the same as in the modulators for the satellite (DVB-S), and the cable (DVB-C) standard. The subsequent inner error protection process is only needed for satellite and terrestrial transmissions. The blocks identified by the gray overlay are specific to DVB-T.

A. *Energy Dispersal and Synchronization*

The data at the base band interface is combined with the bit stream of a pseudorandom noise generator which is implemented by a feedback shift register. The aim of this operation is to achieve a flat power-density spectrum. Only the sync byte of the TS packets is left untouched in order to retain a means for synchronization. The pseudorandom noise generator is reinitialized with a predetermined bit pattern every eighth TS packet. Decoders are informed about the starting point of the sequence by means of an inverted sync byte.

B. *Error Protection and Modulation*

The outer error protection is implemented with a byte-oriented block code. For each block—i.e., the TS packet—error correcting bits are calculated. The result is a block of correction bytes that is appended to the TS packet. The block code that is used is a Reed–Solomon (255 239) code. That means that 16 correction bytes are appended to the 239 information bytes. Since the TS packet has a length of only 188 B, the first 51 B are set to zero and are not transmitted. In this way a Reed–Solomon (204 188) code has been created. If the input

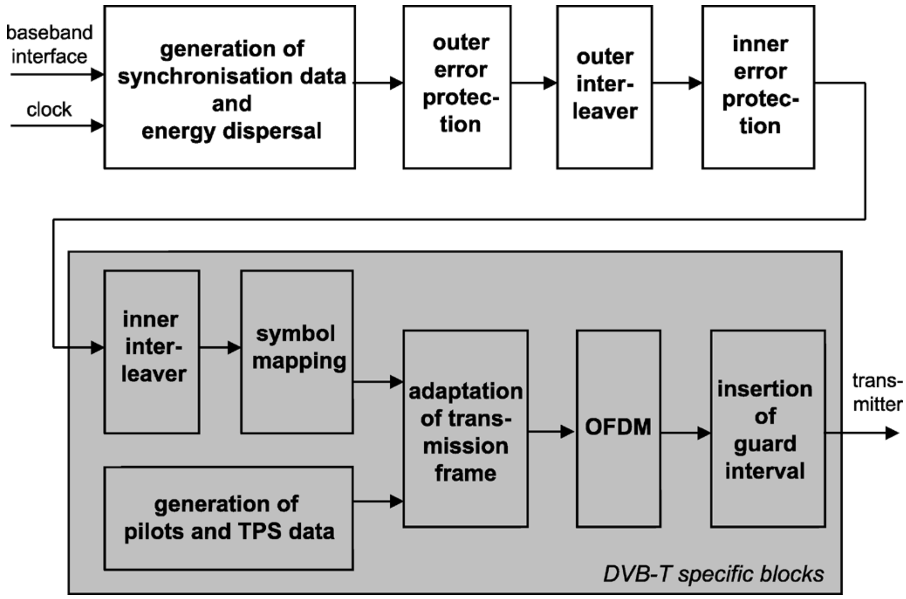

Fig. 2. Block diagram of a DVB-T encoder.

bit-error rate is less than $2 \cdot 10^{-4}$, this code is able to reduce the bit-error rate to about 10^{-11} while in the simplest case correcting up to 8 B per TS packet [6].

The outer interleaver that follows does not provide any additional error correction capability but rearranges bytes in order to facilitate the correction of long burst errors. A block interleaver that reads the bytes into a storage matrix line by line and is read out column by column would be one possible implementation. Such a block interleaver shows disadvantages regarding storage capacity required, synchronization, and sensitivity against periodic disturbances [6]. Therefore, DVB uses a convolutional interleaver with an interleaving depth of $I = 12$ and a base delay of $M = 17$. The convolutional interleaver consists of $(I-1)$ shift registers with the lengths $M, 2M, \ldots, (I-1)M$, respectively. Hence, adjacent bytes are separated by at least 204 B and the total delay is $M \cdot (I-1) \cdot I$ for all symbols.

For DVB-S and DVB-T, an inner error protection follows which is optimized for the correction of bit errors. A convolutional encoder with a basic code rate 1/2 is used for this purpose. For each individual bit of input data two bits are calculated as output data. The data stream is fed into a shift register bit by bit and two output bit streams are obtained by combining the various taps of the shift register. The high amount of redundancy that results from the code rate 1/2 (50%) can be reduced by a puncturing mechanism. This simply means that not all of the calculated output bits are transmitted. If for example every third bit is not transmitted than the residual code rate is 3/4 instead of 1/2. DVB has specified the code rates 1/2, 2/3, 3/4, 5/6, and 7/8.

The next processing element used in the DVB-T system is an inner interleaver [1], which follows the inner error protection. Its purpose is to cope with the effect of frequency-selective channels which may for example result from echoes on the transmission path [6]. The inner interleaver is specified in such a way that it provides optimum performance at a given complexity and memory size. It consists of a combination of a bit and a symbol interleaver. In the bit interleaver 126 successive bits are first combined into a block and are then interleaved within this block. Subsequently the symbol interleaver which is a pseudorandom sequence interleaver changes the sequence of these symbols. The result of this interleaving on the DVB-T signal is frequency interleaving inside one DVB-T symbol.

The inner interleaving process is followed by the symbol mapping. Each of the individual useful carriers of the OFDM signal is separately modulated. A choice can be made between the modulation techniques QPSK, 16-QAM and 64-QAM [1]. The allocation of either two or four or six sequential bits to one carrier is carried out using Gray coding.

The DVB-T system offers the possibility of hierarchical modulation. This means that two independent data streams can be transmitted in the same signal using different modulation techniques like for example QPSK for one (high priority) stream and 16-QAM for the second (low priority) stream. Consequently the robustness against transmission errors is different for the two streams. The high-priority stream enables relatively low data rates to be transmitted in such a way that they can still be received in the case of relatively poor carrier-to-noise ratios. In contrast the low-priority stream enables the transmission of considerably higher data rates, however with higher carrier-to-noise ratio requirements.

C. Coded Orthogonal Frequency Division Multiplexing (COFDM)

The terrestrial channel is very different from both the satellite and the cable channel and may be impaired by severe multipath propagation resulting from the structure of the terrain and buildings. During the development of the DVB-T system mobile reception was not made a requirement but the system was to be able to cope with some time variance

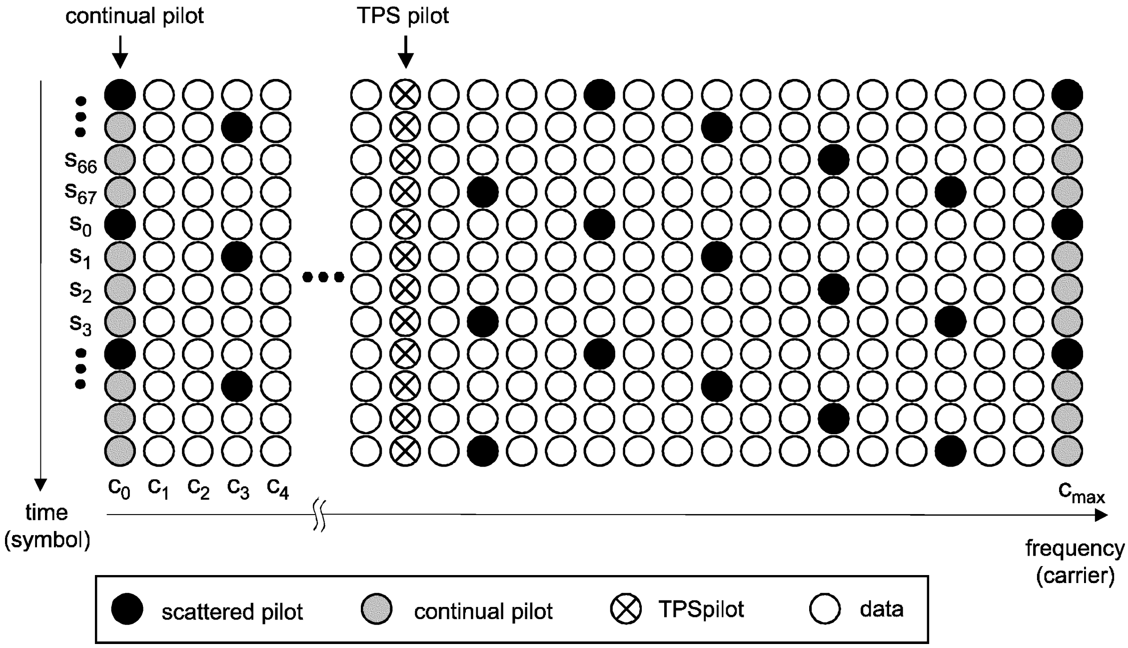

Fig. 3. Transmission frame for the DVB-T signal.

in the channel due to moving objects. It was found that the most suitable modulation system for such channel conditions is COFDM. COFDM copes very well with multipath propagation conditions and offers a high degree of frequency economy by allowing the use of SFNs.

"OFDM" describes how the data stream is allocated to individual carrier frequencies and "C" stands for coding—forward error correction is meant by this. COFDM is characterized by the existence of symbols which consist of a large number of carriers. Thereby each carrier only transports a moderate bit rate. Individual carriers are orthogonal to each other. To calculate the OFDM symbols the inverse fast Fourier transform (IFFT) algorithm is used [6]. The COFDM symbol defined for DVB-T consists of either 6817 carriers in the so-called 8K mode or 1705 carriers in the 2K mode [1].

The start of every COFDM symbol is preceded by a so-called guard interval. The purpose is to enhance immunity to echoes and reflections. As long as the echoes fall within the guard interval they will not affect the receivers ability to safely decode the useful data. The longer the guard interval is the higher will be the echo delays that can be tolerated. The guard interval consists of a cyclic continuation of the useful symbol and its length relative to the duration of the useful symbol may have four different values: 1/4, 1/8, 1/16, or 1/32.

In the DVB-T system the OFDM symbols are combined to a transmission frame. Each transmission frame consists of 68 consecutive symbols. Four consecutive transmission frames constitute a super frame. An illustration of the DVB-T frame structure of 68 OFDM symbols per frame is given in Fig. 3.

In addition to the useful information data a transmission frame includes reference signals for the channel equalization by the receiver, so-called continual pilots and scattered pilots. These pilots are transmitted with an amplitude which is 1/0.75 larger than the amplitude of the other carriers in order to be particularly robust against transmission errors. Furthermore, Transmission Parameter Signaling (TPS) pilots are included. They inform the receiver about the actual operating parameters. The TPS carries are modulated by means of a differential binary phase shift keying (DBPSK). Thus, one bit per carrier can be transmitted. Consequently, one OFDM frame contains a TPS block of 68 bits, namely, 1 initialization bit, 16 synchronization bits, 37 information bits, and 14 redundancy bits for error protection [1]. In order to make the TPS data more robust against frequency-selective channel distortions it is transmitted totally redundantly on 17 carrier frequencies for the 2K mode and on 68 carrier frequencies for the 8K mode.

Table 1 summarizes the main parameters and the options of the DVB-T system—hierarchical modes are not included. Note that some of the values are rounded values. The total symbol duration equals the sum of the duration T_{want} and the duration of the guard interval.

Finally it should be mentioned that mega-frame initialization packets (MIPs) can be inserted in a DVB-T TS [7]. These specific TS packets can be used to address individual transmitters of an SFN. Especially the transmitter time offset function is of interest, since different makes of transmitter products may be used in one SFN which may have different internal processing delays. The time offset also allows optimizing the coverage of the network, since self-interference can be avoided within the service area when the time offset of the individual transmitters in the SFN is properly adjusted.

IV. Performance

Three different criteria shall be used to evaluate the performance of DVB-T: the available useful data rate, the

Table 1
Choice of Parameters for Non-Hierarchical DVB-T Transmission

OFDM mode		**2K**			**8K**		
Number of carriers K		1705 (0 .. 1704)			6817 (0 .. 6816)		
Bandwith of RF channel		**6 MHz**	**7 MHz**	**8 MHz**	**6 MHz**	**7 MHz**	**8 MHz**
Spacing K_0 and K_{max}		5,71 MHz	6,66 MHz	7,61 MHz	5,71 MHz	6,66 MHz	7,61 MHz
Carrier spacing		3348 Hz	3906 Hz	4464 Hz	837 Hz	977 Hz	1116 Hz
Duration T_{want}		299 µs	256 µs	224 µs	1195 µs	1024 µs	896 µs
Guard Interval	**1/4**	75 µs	64 µs	56 µs	299 µs	256 µs	224 µs
	1/8	37 µs	32 µs	28 µs	149 µs	128 µs	112 µs
	1/16	19 µs	16 µs	14 µs	75 µs	64 µs	56 µs
	1/32	9 µs	8 µs	7 µs	37 µs	32 µs	28 µs
Carrier modulation		**QPSK, 16-QAM, 64-QAM**					
Inner code rate		**1/2, 2/3, 3/4, 5/6, 7/8**					

Table 2
Useful Data Rates [Mb/s]

Modulation	**Code rate**	**Guard interval**											
		1/4			**1/8**			**1/16**			**1/32**		
		bandwidth [MHz]			**bandwidth [MHz]**			**bandwidth [MHz]**			**bandwidth [MHz]**		
		6	**7**	**8**	**6**	**7**	**8**	**6**	**7**	**8**	**6**	**7**	**8**
QPSK	**1/2**	3,73	4,35	4,98	4,14	4,83	5,53	4,39	5,12	5,85	4,52	5,27	6,03
	2/3	4,97	5,80	6,64	5,52	6,45	7,37	5,85	6,83	7,81	6,03	7,03	8,04
	3/4	5,59	6,53	7,46	6,22	7,25	8,29	6,58	7,68	8,78	6,78	7,91	9,05
	5/6	6,22	7,25	8,29	6,91	8,06	9,22	7,31	8,53	9,76	7,54	8,79	10,05
	7/8	6,53	7,62	8,71	7,25	8,46	9,68	7,68	8,96	10,25	7,91	9,23	10,56
16-QAM	**1/2**	7,46	8,70	9,95	8,29	9,67	11,06	8,78	10,24	11,71	9,04	10,55	12,06
	2/3	9,95	11,61	13,27	11,05	12,90	14,75	11,70	13,66	15,61	12,06	14,07	16,09
	3/4	11,19	13,06	14,93	12,44	14,51	16,59	13,17	15,36	17,56	13,57	15,83	18,10
	5/6	12,44	14,51	16,59	13,82	16,12	18,43	14,63	17,07	19,52	15,08	17,59	20,11
	7/8	13,06	15,24	17,42	14,51	16,93	19,35	15,36	17,93	20,49	15,83	18,47	21,11
64-QAM	**1/2**	11,19	13,06	14,93	12,44	14,51	16,59	13,17	15,36	17,56	13,57	15,83	18,10
	2/3	14,92	17,41	19,91	16,58	19,35	22,12	17,56	20,49	23,42	18,09	21,11	24,13
	3/4	16,79	19,59	22,39	18,66	21,77	24,88	19,76	23,05	26,35	20,35	23,75	27,14
	5/6	18,66	21,77	24,88	20,73	24,19	27,65	21,95	25,61	29,27	22,62	26,39	30,16
	7/8	19,59	22,86	26,13	21,77	25,40	29,03	23,05	26,89	30,74	23,75	27,71	31,67

carrier-to-noise (C/N) ratio required for quasi-error-free reception and the field strength required for different reception modes.

All possible useful date rates for DVB-T are listed in Table 2. It gives a good overview about the flexibility of the DVB-T standard. Depending on the commercial and user requirements in each country a suitable parameter set can be chosen from the multitude of parameter settings available. For example, a decrease in the length of the guard interval leads to a corresponding increase in the date rate. A similar result will be produced by an increase of the code rate. However, the guard interval used influences the admissible transmitter spacing in SFNs at the same time. Therefore, the length of the guard interval needs to be primarily chosen in view of the required network structure.

In Table 3 the minimum C/N ratio required for quasi-error-free reception is shown. The values are based on simulations of the system behavior and were computed on the assumption that a perfect correction of the channel frequency response has taken place [1]. The Gaussian channel is characterized by one direct signal path from transmitter to receiver. The only impairment present is additive white Gaussian noise (AWGN). In order to describe the impairment caused by echoes the Ricean channel is defined, which takes into account the effect of multipath signals in addition to AWGN. A dominant direct signal path is present. A transmission channel with echoes of more or less equal significance and without any direct signal path is called Rayleigh channel. It can be seen that the required C/N ratio increases with the complexity of the transmission channel. The combination of Tables 2 and 3 indicates that the higher

Table 3
Minimum C/N Ratio in the Transmission Channel

Modulation	Code rate	Gaussian channel [dB]	Ricean channel [dB]	Rayleigh channel [dB]
QPSK	1/2	3.1	3.6	5.4
	2/3	4.9	5.7	8.4
	3/4	5.9	6.8	10.7
	5/6	6.9	8.0	13.1
	7/8	7.7	8.7	16.3
16-QAM	1/2	8.8	9.6	11.2
	2/3	11.1	11.6	14.2
	3/4	12.5	13.0	16.7
	5/6	13.5	14.4	19.3
	7/8	13.9	15.0	22.8
64-QAM	1/2	14.4	14.7	16.0
	2/3	16.5	17.1	19.3
	3/4	18.0	18.6	21.7
	5/6	19.3	20.0	25.3
	7/8	20.1	21.0	27.9

the useful data rate the higher the requirements with respect to the C/N ratio.

Thorough investigations were carried out in many countries of the world in order to derive the required minimum field strengths (and thus the key parameter for network planning) from the C/N ratios listed above. Results of these investigations are documented in the resolutions of the first session of the regional radiocommunication conference (RRC '04) [8]. The basic idea was to define four types of reception. These are stationary reception with a rooftop antenna, portable reception outside buildings, portable reception inside buildings and mobile reception. The practical experience made when receiving DVB-T signals in cars is described in Section V-A.

The main differences between the four types of reception are the antenna height (10 m versus 1.5 m) which results in a height loss or height gain of between 12 and 18 dB, the frequency-dependent antenna gain which differs among the antenna types ($7 \ldots 12$ dB versus $-2 \ldots 0$ dB) and the building penetration loss which has been assumed to be about 8 dB. Based on these figures the minimum median equivalent field strength values have been calculated for a location probability of 50%, 70%, and 95%. This is the percentage of locations within a small area (typically 100 m $\times$ 100 m) that is covered. For analogue transmission a location probability of 50% was considered acceptable, since there was a graceful degradation of picture quality at the border of the coverage area. For digital transmission a location probability of 95% should exist for a good coverage.

Subsequently, a required C/N ratio of 14 dB is assumed. This corresponds to a 16-QAM modulation scheme with a code rate of 2/3 in a Rayleigh channel. An implementation margin of another 3 dB is added. The result according to the RRC '04 report [8] is then that field strength values of between 50 and 54 dBμV/m are required for stationary reception, between 73 and 79 dBμV/m for portable outdoor and mobile reception and between 85 and 91 dBμV/m for portable indoor reception in the UHF range (470–862 MHz). In the VHF range (174–230 MHz) 46 dBμV/m, 65 dBμV/m and 75 dBμV/m are recommended for stationary, portable outdoor, and portable indoor reception, respectively.

Nevertheless, more actual experience and practical measurements in Germany have shown that these figures should not be used for network planning. The field strength values given for the stationary reception are probably valid for noise-limited networks. But the reality is that the new digital frequency plan as a result of the ITU regional radiocommunication conference in May 2006 (RRC '06) will be based on interference-limited allotments or assignments. Otherwise the plan would be very frequency-inefficient. This fact should be taken into account by adding at least 3 dB to the field strength values mentioned above for stationary reception. The measurements in Germany have also shown that the allowances for man-made noise (2 dB in the VHF range, 0 dB in the UHF range) that are considered in the RRC '04 report [8] are too optimistic, especially for indoor reception at VHF frequencies. Furthermore, the antenna gains of indoor antennas available in the market are in many cases worse than expected. And finally, the building penetration loss is sometimes higher than assumed. Considering these aspects the minimum field strength for stationary reception in the UHF range will be around 55 dBμV/m. For portable outdoor and mobile reception around 75 dBμV/m and for portable indoor reception around 90 dBμV/m will have to be considered. The corresponding figures for VHF frequencies are 50, 65, and 87 dBμV/m. That means that the minimum field strength for portable indoor reception of VHF channels is only about 3 dB lower than that required for a medium UHF channel.

Note that these values relate to 16-QAM with a code rate of 2/3. They have to be adapted to the DVB-T parameters chosen on a case by case basis.

Another important aspect is, that a minimum field strength of about 90 dBμV/m for portable indoor reception does not automatically mean that the transmission power of existing transmitters for analogue television will need to be increased. Just the opposite is true since field strength values of higher than 90 dBμV/m already exist in the vicinity of analogue transmitter sites today. If the network is supposed to provide for portable indoor reception all over the country then the usage of 16-QAM modulation and the building of a network with several transmitters with relatively low power is the appropriate way of doing it. Compared to the analogue networks, this would not increase the maximum field strength values but instead would create a rather homogeneous field strength all over the coverage area.

V. Mobile Reception

Compared to the traditional stationary reception for which a rooftop antenna at 10-m height is assumed, mobile reception is much more difficult to realize. A loss in antenna gain of approx. 10 dB and a loss in field strength of more than 10 dB resulting from the low antenna height of about 1.5 m has to be taken into account [8]. Furthermore, the transmission channel is not characterized by just one direct and dominant signal path, but by multiple fast changing echo signals. These multipath signals can mathematically be described as a time-varying Rayleigh channel and require a higher carrier-to-noise ratio than needed for stationary reception [1]. A specialty of mobile reception is the Doppler effect which is a frequency shift in the signals arriving at the receiver. The extent of the shift depends on the frequency itself and on the relative speed between the transmitter and the receiver.

To achieve successful mobile DVB-T reception, a number of factors need to be considered. The receiver needs to track channel variations in time and frequency. In addition, correct channel estimation needs to be provided. Moreover the receiver has to be able to compensate for noise-like distortions called FFT leakage which are caused by the nonorthogonality of the DVB-T subcarriers due to the time varying channel. The network needs to provide high enough field strength and C/N ratio at a sufficiently high number of locations to permit a reliable mobile service. Consequently, both the network and the receiver have to be well suited for mobile reception.

A. Network Design

Over a number of years, research on mobile reception of DVB-T signals was carried out in Germany. An early result of this research—in 2001—was the understanding that networks able to offer portable indoor reception will automatically support mobile reception [9]. This result was based on practical tests using first generation DVB-T car receivers. Fully optimized car receivers became available in 2003 and resulted in the finding that flawless mobile reception can be achieved in networks which have been optimized for just portable outdoor reception.

For portable indoor, portable outdoor, and mobile reception, SFNs are recommended. They result in a more homogeneous distribution of field strengths between the transmitters. Due to the fact that signals in SFNs originate at various locations "network gain" is created. Many locations which are severely affected by shadowing of the signal coming from one transmitter can receive a signal from one of the other transmitters. Inside the coverage area of an SFN no retuning of the reception frequency is required.

B. Diversity Techniques for Mobile Receivers

In order to provide optimum mobile reception in an existing DVB-T network antenna diversity techniques to combat the effects of signal fading can be used. The basic idea underlying diversity reception is that if two or more reception antennas—called diversity branches here—are appropriately installed, signal fading affecting the two antennas will be uncorrelated. It follows that a signal composed of a suitable combination of samples of the signals received by the various antennas will exhibit less fading effects than the signals provided by each individual antenna. In the following, suitable methods for antenna diversity will be described. They belong to the family of space diversity techniques [10], [11]. Under certain circumstances, these techniques can be adapted to a DVB-T receiver.

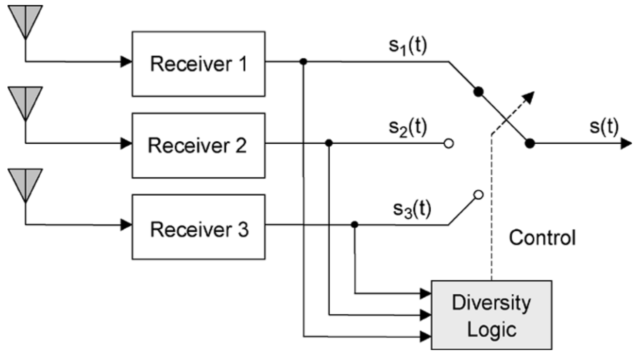

Fig. 4. SC.

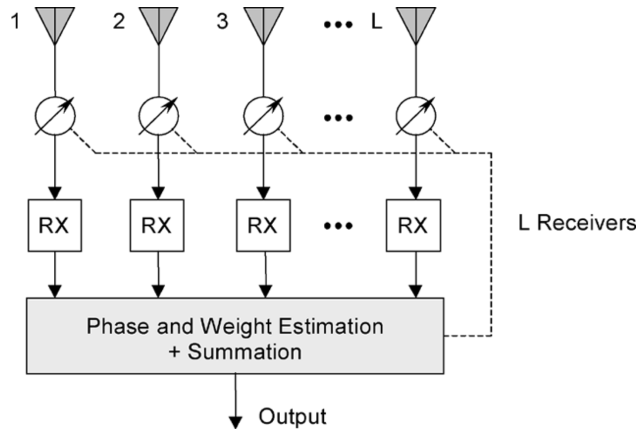

Fig. 5. MRC.

1) Selection Combining (SC): With SC, the signals of L diversity branches are fed into a so-called diversity logic. The diversity branch with the highest carrier-to-noise-ratio is selected. Its signal is forwarded to the demodulator. The principle of selection combining is shown in Fig. 4 for a system with $L = 3$ diversity branches.

A variety of decision criteria which may be used by the diversity logic are conceivable. The classical approach known from mobile receivers for inherently broad-band analogue signals is based on the assumption of a non-frequency-selective Rayleigh channel to guarantee local coherence of the received signals. A DVB-T signal consists of a large number of narrow-band OFDM subcarriers. These subcarriers can be evaluated individually. For selection combining, the subcarriers with the highest signal-to-noise ratio will be selected from the three sets of subcarriers available from the three branches. Since the noise level in the three branches can be seen as identical the signal power itself is used for the selection process. It can be derived from the channel transfer coefficients obtained by the channel estimation. Selection combining can alternatively be executed on the bit stream leaving the symbol deinterleaver. For the selection of a diversity branch the signal power needs is used again. It is finally possible to apply selection combining on the TS level. This method is easily implemented with existing chip-sets which have not been developed specifically for diversity receivers. The TS is controlled by a diversity logic. Incorrect MPEG-2 packets are replaced by correct packets provide by one of the other diversity branches.

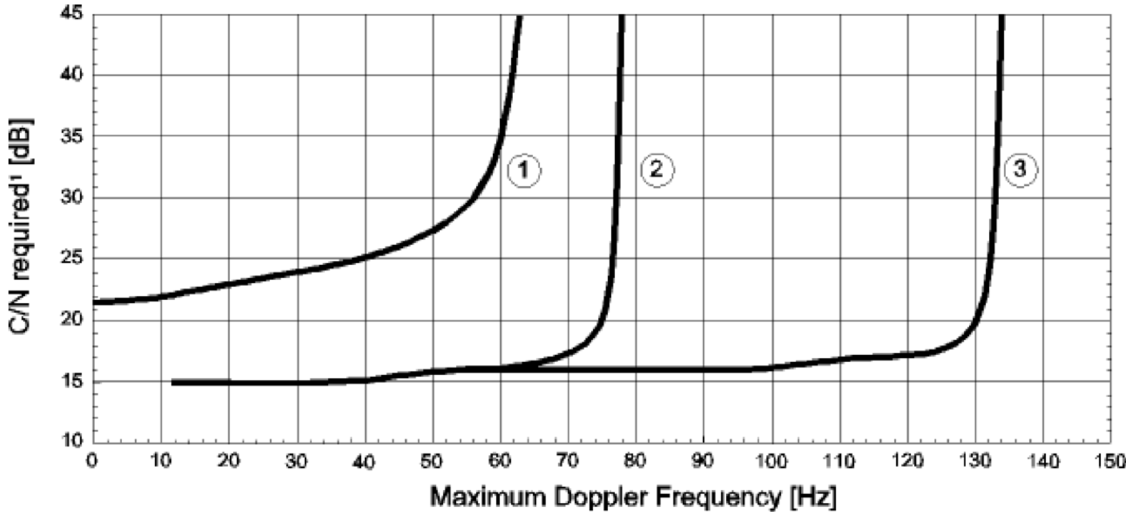

Fig. 6. The effect of antenna diversity on mobile reception. (8k mode, 16 QAM, Tg $= 1/8$, $R2 = 2/3$, TU6). 1: single antenna with chipset optimized for stationary reception. 2: MRC antenna diversity with first generation chipset optimized for mobile reception. 3: MRC antenna diversity with second generation chipset optimized for mobile reception.

2) Maximum Ratio Combining (MRC): With MRC, the signals of L diversity branches are first synchronized in phase. They then receive an individual weight according to the momentary signal-to-noise ratio in the individual branch. In a second step the weighted and cophased signals are added. Theoretically, this technique is considered to be optimum in the sense that it yields better statistical reduction of fading of than any other linear diversity technique. In Fig. 5 this method is shown.

Like with selection combining, different processing levels are possible. The most efficient method works on a subcarrier level. The required phase and weight estimation can be achieved by a multiplication with the conjugate complex of the transmission factor.

The benefits of antenna diversity have thoroughly been investigated by means of simulations and field tests. These investigations were carried out using the "German" DVB-T parameters which can be described by the following set (8K, 16-QAM, code rate 2/3, $\Delta = 1/4$). A very critical channel which is referred to as the typical urban (TU6) profile is used to demonstrate the results of the investigations.

In Fig. 6 the abscissa shows the maximum Doppler Frequency f_D which is a measure of the driving speed v. It is proportional to the speed of light c. The maximum Doppler frequency is a function of the carrier frequency f_0 used in the broadcast channel

$$v = \frac{f_D}{f_0} \cdot c \quad f_0 : \text{carrier frequency}.$$

Thus a Doppler frequency of 80 Hz results when driving either at 101 km/h receiving UHF channel 69 or when driving at 182 km/h receiving UHF channel 21.

According to Fig. 6, a stationary receiver with only one antenna requires a C/N of approx. 22 dB for perfect reception. The use of MRC antenna diversity lowers the required C/N ratio at low Doppler frequencies by about seven dB. More important is the extension of the speed limitations due to the effects of antenna diversity. The second generation chipset shown in Fig. 6 requires a C/N of only 20 db at a maximum Doppler frequency of 130 Hz. Therefore, even DVB-T signals transmitted in the highest UHF channel (69) can be received flawlessly at driving speeds up to 164 km/h. Further improvements in car-receiver implementations have been made. Using optimized preamplifiers the effective noise figure was reduced to some 2 dB—a value significantly lower than the value of 7 dB used for the original DVB-T network planning [15]. In consequence, in the German 8K network we no longer experience any practical limitations to perfect DVB-T reception in cars. In fact, various car manufacturers offer factory-installed and after market DVB-T receivers for their products.

C. Handover Techniques for Mobile Receivers

Tuning of stationary receivers is relatively simple. Only one single-frequency scan is necessary to identify all available channels. If useful levels of field strength are detected in the channels scanned the receiver will try to synchronize to the received signal. Non-DVB-T signals can thus be excluded. The TPS data will be read if synchronization could be achieved and used for demodulation and decoding.

For mobile receivers the tuning process is much more complex. The receiver has to perform an automatic frequency change if the field strength of the actual signal decreases at the border of the coverage area. Furthermore, the interruption during this frequency change—the handover—should be as short as possible. Therefore, DVB has specified specific data as proposed in [16] to support handover.

The idea is to divide the coverage area of a network into several cells (Fig. 7). A cell is defined as a geographical area in which a certain TS is delivered on a certain frequency. The cell can be covered by means of a single transmitter or by

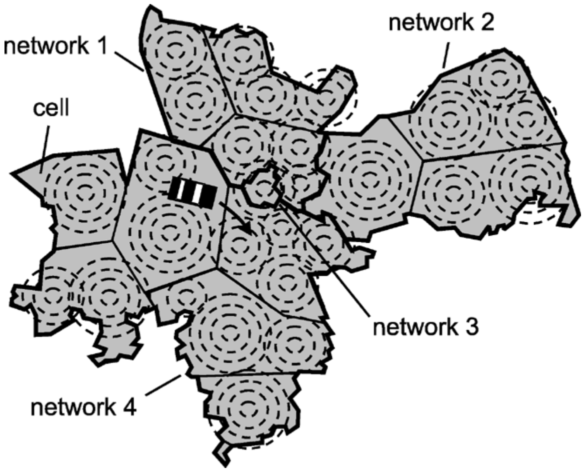

Fig. 7. Cell structure within a DVB-T network.

means of an SFN network. Each cell is identified by an identifier called cell_id which has a length of 16 bits. Since the TS itself may be identical in neighboring cells, it cannot include information that differs from one cell to another. Thus, the cell_id was included in the TPS data [1]. When decoding the TPS data mobile receivers will read the cell_id and determine the cell the actual signal comes from.

For each network that is listed in the NIT included in the TS a cell_list_descriptor should be present. In this descriptor all cells of the network are described by means of spherical rectangles defined by the geographical coordinates of one corner and the difference in latitude and longitude of the opposite corner [5]. A more accurate description of the cells is not needed. In the second loop of the NIT the cell_frequency_link descriptor should be present. It combines the information about alternative frequencies and the cells in which these frequencies are used. As a result the NIT provides the complete information about which frequency is used for which TS in which region.

A flexible and efficient handover algorithm that is based on these data elements has been introduced in [17]. Before a handover can be executed the mobile receiver needs to determine its actual location as accurately as possible and it needs to prepare lists including the alternative frequencies for at least the actual service. Ideally, location information will be derived from a satellite based positioning system like GPS. If GPS data are not available the cell_id in the TPS data can be read. The cell_list_descriptor will then help to roughly determine the actual position. The list of alternative frequencies should be compiled on a service oriented basis since the service of interest may not only be present in the actual TS of the actual network but also in other TSs of for example adjacent networks. Thus, the receiver will use the service_list descriptor to identify the service and will look for that service not only in the cell_frequency_link_descriptor of the actual TS, but also of all other transport_streams. The collection of alternative frequencies for the actual service will then be reduced to the relevant ones using the information about the current location. If GPS data are available only one or two frequencies will be retained. If just the cell_id is known the frequencies of up to six neighboring cells have to be kept in the list. The neighboring cells are those having an overlap with the actual cell. The test condition for an overlap is [17]

$$\mathrm{E}_{\mathrm{test}} > \mathrm{W}_{\mathrm{actual}} \text{ and } \mathrm{W}_{\mathrm{test}} < \mathrm{E}_{\mathrm{actual}} \text{ and } \mathrm{N}_{\mathrm{test}} > \mathrm{S}_{\mathrm{actual}} \text{ and } \mathrm{S}_{\mathrm{test}} < \mathrm{N}_{\mathrm{actual}}$$

W stands for the longitude of the western cell border, N for the latitude for the northern cell border, and so on. The index "actual" marks the actual cell, the index "test" one of the other cells that are tested regarding an overlap. The reduction of the list of alternative frequencies may be followed by ordering such frequencies by the probability of them becoming relevant during the travel. Criteria for the ordering may be the extent of overlap, the size of the adjacent cell or the history of the usage of alternative frequencies.

When the mobile receiver reaches the border of a cell the detected field strength of the actual signal will decrease. The receiver will briefly tune to the alternative frequencies that have been kept in the list in order to identify available alternative channels and the reception quality of those channels. If the bit error rate of the actual signal exceeds a critical value the receiver will tune to the best available channel and will start the decoding process. It will first read the PAT which is repeated every 100 ms and will check whether the service of interest is available or not. Especially if many alternative frequencies have been left in the list, there is a risk that the alternative frequency just tuned to is not used for the actual service [16]. Tuning failures like this will lead to a clearly visible interruption of the service and should therefore be avoided by prefiltering the alternative frequencies as described above.

The basic handover procedure described so far can be enhanced if additional tuners are available in the receiver. This will be the case for most of the mobile receivers since antenna diversity techniques are used. Additional tuners might be used for detecting alternative frequencies with acceptable field strength and for reading the TPS data of these frequencies in advance. Thus, the risk of tuning failures can be eliminated and service interruptions minimized [18].

VI. Germany as a Case Study

The United Kingdom is currently the country of the world with the largest number of DVB-T homes. In June 2005 that number had exceeded 5 million. Despite this very impressive result the switchover from analogue to digital terrestrial TV is supposed to last until 2012.

In contrast, Germany started a rapid switchover from analogue terrestrial TV to DVB-T in 2003. In order to understand the reasoning behind this process, one needs to take into account that the percentage of households which used analog terrestrial TV reception for their primary TV sets had dropped to less than ten before DVB-T was introduced. More and more people had moved to cable or satellite. The main reason for this move was the relatively low number of TV services that could be received terrestrially. In some regions noisy pictures may also have been an argument against the rooftop antenna. On the other hand unlike in many countries of the world some 80 German free-to-air TV programs and some 60 free-to-air radio programs can be received via satellite (DVB-S).

In this situation the broadcasters had only two options, either to stop terrestrial broadcasting altogether or to introduce DVB-T immediately in order to overcome the deficiencies of the analogue terrestrial networks.

In 2002, the second option was chosen and DVB-T was launched in Berlin, the nation's capital, and in the region surrounding it. Four months after the start of the first two DVB-T multiplexes all commercial broadcasters discontinued their analogue service. Another five months later, all analog services stopped. Seven DVB-T multiplexes each delivering four services are on air now.

The Berlin switchover was a great success. Thus, other regions of Germany followed in 2004 and 2005. The "German model" has four special characteristics. Firstly, the DVB-T networks are designed in such a way that portable indoor (and mobile) reception is offered in densely populated areas. Secondly, the number of TV services offered via DVB-T is at least twice the number of the former analog terrestrial TV services. Thirdly, all services are free-to-air. And finally, the most important aspect of the model is the rapid switchover similar to the model described for Berlin. The general concept for Germany is to follow this model region by region so that the migration from analogue terrestrial to DVB-T—which takes only a few months within one region—will be finished all over the country not later than 2010, probably as early as 2008.

It is the combination of a rapid switchover and the creation of sizeable SFNs which made it possible to allocate enough frequency channels to DVB-T in order to be able to start with four to six DVB-T multiplexes in each region. For sizeable SFNs to become feasible and in order to support portable indoor reception the modulation parameters chosen are the 8K mode with 16-QAM. The relative length of the guard interval is usually 1/4, the code rate of the inner FEC was selected as 2/3. Consequently, a data rate of 13.27 Mb/s is available for most of the multiplexes. For multiplexes transmitted in the VHF band with its channel spacing of 7 MHz or for regional multiplexes, slightly different values have been chosen. Most of the multiplexes carry four TV services.

In summary, the German example shows that a rapid switchover is possible. No government ruling was required to make broadcasters discontinue the analog transmissions. Instead, the introduction of DVB-T was the result of multilateral agreements by commercial and public broadcasters media authorities network operators etc. The public was well informed about the plans and the benefits to be expected from the change from analogue to digital. Most of the people accepted the advantages of DVB-T regarding the large number of services, the enhanced picture quality and the possibility to consume TV anywhere. The reception by means of small indoor antennas seems to be very attractive—even more so for additional TV sets installed around the house. Set-top boxes with and without built-in hard disk, TV sets with integrated DVB-T receivers, plug-in modules for PCs and laptops, as well as DVB-T receivers with a USB interface have become a reality. High-end cars are being equipped with DVB-T receivers. Taxi drivers are able to watch DVB-T on built-in or portable devices while waiting for their passengers. It is expected that by the end of 2005—about three years after the start of the first regular DVB-T services in and around Berlin—some 3 million receivers will have been sold in the country. More than 50 million people will then live in regions covered by DVB-T networks—some 60% of the German population. The introduction of DVB-T has led to a rebirth of terrestrial TV in the country. This fact is best proven by the figures in the region of Bremen. The percentage of terrestrial households grew from some 9% before the DVB-T launch to 17% just one year after the launch. In practically all cases DVB-T replaced cable.

REFERENCES

[1] *Digital video broadcasting (DVB); Framing structure, channel coding and modulation for terrestrial television*, European Standard (EN) 300 744 V1.5.1, European Telecommunications Standards Institute (ETSI), Nov. 2004.

[2] "Modellversuch DVB-T Norddeutschland (Interim Report)," Braunschweig, Germany, Mar. 2001.

[3] *Information technology—Generic coding of moving pictures and associated audio*, ISO/IEC International Standard IS 13818, Nov. 2004.

[4] U. Ladebusch, *Einführung in den Datenrundfunk, Teil 1 + 2, Fernseh und Kinotechnik (FKT)* vol. 52, pp. 323–330, 425-432, Jun./Jul. 1998.

[5] *Digital video broadcasting (DVB); Specification for service information (SI) in DVB systems*, European Standard (EN) 300 468, European Telecommunications Standards Institute (ETSI), May 2003.

[6] U. Reimers, *DVB—The family of international standards for digital video broadcasting*, 2nd ed. Berlin, Germany: Springer-Verlag, 2005.

[7] *Digital video broadcasting (DVB); DVB mega-frame for single frequency network (SFN) synchronization*, Tech. Specificat. (TS) 101 191 V1.4.1, European Telecommunications Standards Institute (ETSI), Jun. 2004.

[8] International Telecommunication Union (ITU), "Resolutions of the first session of the RRC planning of the digital terrestrial broadcasting service in parts of regions 1 and 3, in the frequency bands 174–230 MHz and 470–862 MHz," Geneva, Switzerland, May 2004.

[9] A. Roy and C. Liss, *Mobilempfang von DVB-T-Signalen—Messungen und Stand der Empfängertechnik, Fernseh und Kinotechnik (FKT)* vol. 56, pp. 112–115, Mar. 2002.

[10] D. G. Brennan, "Linear diversity combining techniques," *Proc. IRE* vol. 47, no. 6, pp. 1075–1102, Jun. 1959.

[11] J. D. Gibson, *The Mobile Communications Handbook*. Boca Raton, FL: CRC, 1996.

[12] Commission of the European Communications, Information Technology and Sciences, "Digital land mobile radio communications," COST 207, Final Rep., 1989.

[13] A. Roy, "Digitales Fernsehen im Kraftfahrzeug," presented at the IMA 2004—Informationssysteme für mobile Anwendungen, Braunschweig, Germany.

[14] C. Liss, *Diversity-Empfang für Mobile DVB-T-Systeme, Fernseh und Kinotechnik (FKT)* vol. 56, pp. 18–21, Jan. 2002.

[15] European Conference of Postal and Telecommunication Administrations (CEPT), "The Chester multilateral coordination agreement relating to technical criteria, coordination principles and procedures for the introduction of terrestrial video broadcasting (DVB-T)," Chester, , Jul. 1997.

[16] U. Ladebusch, "Optimierung von Datenstrukturen im digitalen Rundfunk," doctoral thesis, Technical University of Braunschweig, Braunschweig, Germany, 2000.

[17] U. Ladebusch and H. Föllscher, *Hand-Over-Algorithmus für den mobilen DVB-T-Empfang, Fernseh und Kinotechnik (FKT)* vol. 56, pp. 105–111, Mar. 2002.
[18] "Digital video broadcasting (DVB): Guidelines on implementation and usage of service information (SI)," European Telecommunications Standards Institute (ETSI), Tech. Rep. (TR) 101 211 V1.6.1, May 2004.

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