Reconstruction and reciprocal filter of OFDM waveforms for DVB-T2 based passive radar

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***Abstract*—The digital video broadcasting (DVB) transmission standard DVB-T2 published by the ETSI [1] enables a new digital television format for terrestrial transmissions. It currently supersedes DVB-T transmission systems. The introduction of a complicated frame and modulation structure raises several demands to process DVB-T2 in passive radar applications. This includes challenges for the reconstruction and the processing due to different symbol lengths, modulation parameters like the length of FFTs and the overall structure. It is necessary to understand the challenges and accomplish solutions to address these changes. Different solutions were tested by the Fraunhofer FHR passive radar department, Germany for the usage in their PCL systems.**

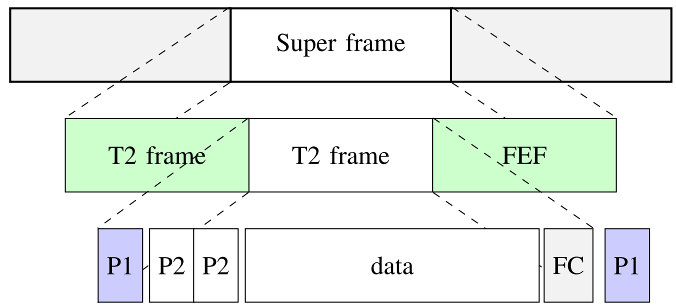


Fig. 1. The frame structure of a DVB-T2 stream

I. Introduction

The widespread availability of broadcasting infrastructure for television and radio enables a wide range of applications. This includes the passive exploitation as a transmitter of opportunity for the detection and tracking of objects like airplanes and ships. This technique is known as passive radar where the transmitter and its infrastructure is not under the control of the radar engineer and the system has to deal with the present signals. Due to recent changes and demands by the broadcasters, digital video broadcasting has reached its second standard DVB-T2. It has already been established in several countries [2] and mostly replaces the previously used DVB-T.

Moreover, the change of the terrestrial television broadcasting standard has been carried out as a switchover in Germany and started in the metropolitan areas on March 29, 2017 [3]. The DVB-T2 infrastructure has been built using the same transmitter sites as for DVB-T with comparable radiated power and similar single-frequency network (SFN) configurations.

II. DVB-T2 structure

The DVB-T2 standard offers an increased maximum data rate by the reduction of redundant overhead, the effective number of pilot carriers, constellations up to 256 QAM and a more efficient forward error correction (FEC) than in DVB-T at the same carrier-to-noise ratio. Commonly, longer OFDM symbol durations can be (and are) used in DVB-T2 systems [4], [5] which reduces the relative timespan of the guard interval (GI) compared to the symbol duration. One additional feature is the specification of several bandwidths between 1.7 and 10 MHz.

A DVB-T2 stream is diverse and built-up in a frame structure. The basic elements are the T2 frames which consist of P1, P2, data and optional frame-closing (FC) symbols at a maximum duration of 250 ms, see Fig. 1. The actual content is encapsulated in one or more physical layer pipes (PLP). Optionally, future extension frames (FEF) might be inserted between two T2 frames for later use [1]. A feature overview is given in e.g. the implementation guidelines [5, pp.17-64].

III. Reconstruction challenges

The transmission structure needs to be known for passive radar processing to perform signal reconstruction. This is performed as demodulation followed by remodulation. The goal is to obtain a noise-free reference signal as an estimate of the originally transmitted signal. For DVB-T2 several features require special treatment which involves an increased effort compared to e.g. DVB-T based processing. In particular, the variable DVB-T2 parameters offer a vast variety of signal configurations which can solely be handled by an adaptive signal processing. In the following, several aspects shall be illustrated which have an influence on the reconstruction and the passive radar processing.

In principle the reconstruction can be implemented on a symbol basis which include multiple modulation types that have to be considered. The more advanced method includes a decoding down to the FEC or PLP level enabling the decoding of rotated constellations, time-interleaving and error protection. Despite the latter solution handling more signal variants, it needs to cover multiple symbols at once and handle this delay.

A. P1 synchronization (P1 detection)

The first step of the decoding procedure is to synchronize to the P1 symbol in the individual frames of the stream. Starting from this point it is possible to retrieve the information needed to decode this frame. The required search range duration is limited to maximal 250 ms and can be coupled to a threshold to detect the presence of DVB-T2 at all, see also [5, p.161].

TABLE I. USEFUL SYMBOL DURATION T_{U} IN 8 MHZ CHANNELS

mode	1k	2k	4k	8k	16k	32k
T_{U}	112 µs	224 µs	448 µs	896 µs	1792 µs	3584 µs
Δf_{sc}	8929 Hz	4464 Hz	2232 Hz	1116 Hz	558 Hz	279 Hz

A modified pre-synchronization algorithm described in [6] provides an easy and stable point of P1 synchronization. It is particularly suitable since it provides a triangle shaped output as an improvement to the method proposed in [5, p.161]. After synchronization, the following P2 and data symbols can be reconstructed and used for passive radar processing.

B. FFT length and guard interval (GI) duration

The indication of the FFT length and GI of the symbols is done in the P1 symbol at the T2 frame start. These will be kept within the frame. Thereby multiple combinations are possible to provide a setup for either robust or high data rate content. The flexibility is critical to the implementation since it needs to handle all cases. This also includes the support of an extended mode which adds up to 160 kHz to be used in 8 MHz channels for sub-carriers in the 8k, 16k and 32k mode [1, p.116]. Furthermore, the GI is signaled unambiguously just in P2 symbols which requires a flexible implementation concept.

In DVB-T2 commonly FFT lengths up to 32768 (32k) are used. This means that the symbol duration is increased compared to the maximum 8k in DVB-T as shown in Table I. This increase supports the already mentioned advantage for the throughput due to a shortened relative GI timespan. The longer averaging time can support the reconstruction in case of impulse like interferences [5, p.28] but will be more sensitive to non-static channel conditions. In addition, the frequency stability and accuracy requirement is increased due to a carrier spacing of just 279 Hz in 8 MHz channels. Longer symbol durations thereby lead to a decrease of the unambiguous Doppler interval for symbol-wise radar processing methods.

C. Mixed frames, future extension frames (FEF)

It is also possible to obtain a DVB-T2 stream with mixed frames which contains different transmission parameters like the FFT length and GI duration. This might be used to embed low data-rate content like SD in HD transmissions or TV and radio. For the reconstruction of mixed frame streams, either the in-band signaling [1, p.32] or the L1 post dynamic [1, p.74] information might be used to speed-up the setup process.

In addition, FEF may be used which might not follow any present standard specifications. The frame shall still start with a P1 symbol [1, p.99] but the remaining content is flexible and the reason for the automatic gain control to be kept constant during the FEF part [1, p.100]. Since the modulation structure might not be known it can mostly not be reconstructed easily. However, in most FEF scenarios at least two 'known' T2 frames ($\leq 500\,ms$) should follow in a row with likely the same FFT length and could be used for regular DVB-T2 processing.

D. Various modulation schemes of PLP, dummy cells and pilots

Every PLP can be configured individually with respect to the used constellation, code rate and time-interleaving depth [5, p.23]. Due to the mapping of the frame mapper and changes in the frequency interleaver, the data cells will be placed in a different sequence to the physical carriers [1, p.100]. Therefore, it is necessary to associate the correct physical carriers before the demodulation process also to handle multiple PLPs with different modulation schemes. The dummy cells which fill up a T2 frame will thereby be BPSK modulated with a PRNG sequence [1, p.99]. Since these carriers are deterministic their values can be precomputed or demodulated by hard decision.

It should be noted that in DVB-T2 five different pilot types and one of eight scattered pilot patterns per input need to be associated correctly, too. For spare pilot patterns a temporal interpolation can be needed [5, p.178], especially for the channel estimation in extended multipath environments.

E. Unmodulated, bias balancing, tone reservation carriers

The increased sub-carrier count achieved by longer FFT lengths causes a growth of the resulting peak-to-average power ratio (PAPR) which might be necessary to be compensated for high-power transmissions. In order to maintain a similar signal power per symbol, the P2 symbols with multiple pilots will always contain PAPR tone reservation (TR) carriers [1, p.168], for other symbols this is optional. These TR carriers will be set to arbitrary complex values and occupy about 1 % of the normal mode carriers. Therefore, the reconstruction approach can be either based on the TR algorithm [1, p.119] or the carrier values are simply filled with complex zeros.

For signals following the DVB-T2 standard version 1.2.1 or later, the TR carriers in P2 symbols will be computed by at least one PAPR iteration [1, p.119] otherwise these will be 'transmitted' with complex zero. If required in the P2 symbols, bias balancing cells will be inserted. Fortunately, the balancing cells are set to exactly one arbitrary value $C_{\mathrm{bal}}(m)$ per T2 frame m [1, p.96] and might be retrieved by recalculation or averaging of the corresponding carrier values.

In FC symbols unmodulated carriers will be inserted due to many pilots by intentionally setting the last $N_{\mathrm{FC}} - C_{\mathrm{FC}}$ cells to zero [1, p.99]. This corresponds to distinct physical carriers and leads to up to 30 % of the in-band carriers being unused.

F. Active constellation extension

The active constellation extension (ACE) described for DVB-T2 signals is another technique to adapt the PAPR. It will shift the outer constellation points to compensate peak power [1, p.83 / 117]. Since the outer points will no longer match the regular QAM constellation as illustrated in Fig. 2, this has to be considered for the reconstruction. For standard version 1.2.1 or later, the ACE is used always for the outer constellation points of carriers holding L1 signaling [1, p.63].

The ACE technique might not be used extensively but its actual usage is signaled. However, ACE might not lead to a signal change for some configurations [1, p.118] but its parameters $V_{\mathrm{clip}} \in [0, 12.7\,\mathrm{dB}], G \in [0, 31], L \in [0.7, 1.4]$ are not broadcasted, see [1], [7]. Probably, the three unknown parameters could still be estimated from a good reference signal and reconstructed with the ACE algorithm. Otherwise, the affected carriers might be handled like without ACE usage, with soft decision or simply be ignored. No investigations on the impact to the passive radar processing performance have

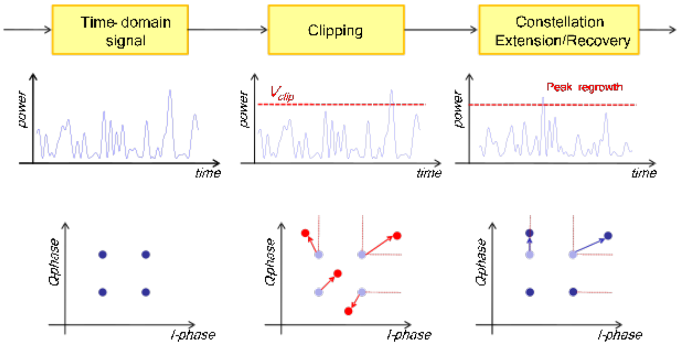


Fig. 2. ACE algorithm © ETSI 2012, reproduced with permission [5, Fig.82]

been carried out so far. The shifted constellation points would also interfere with classical noise measurements [5, p.204].

G. Time interleaving, rotated modulation, LDPC

The low-density parity-check (LDPC) coding can improve the decoding capabilities for low signal levels significantly [5, p.218]. The block code works on individual FEC blocks, the log likelihood-ratio (LLR) demapping should be preferred for the decoding. LLR can be seen as an 1D decision problem for a particular point. The demapping process gets two dimensional for rotated constellations after cyclic Q-delay removal. It can be extended by iterative demapping (ID) which takes a priori information from LDPC decoding into account [5, p.198-204].

Time interleaving was introduced in addition to bit, cell and frequency interleaving, typically over 70 ms [5, p.29]. However, it is also possible to spread cells of a FEC block over many symbols and even into several T2 frames. Latter might cause a significant time-delay for single data cells if FEC should be applied or if the cells' Q-parts are cyclically delayed within one FEC block in case of rotated constellation usage [1, p.50]. The maximum extent of an interleaving frame is limited to the duration of a DVB-T2 super-frame which can be up to 64 s or up to 128 s with FEF parts [1, p.54/86]. The interleaving range can be checked in case of multi-frame interleaving (TIME_IL_TYPE = 1) with the relevant parameter P_{I} (see TIME_IL_LENGTH) [1, p.70]. The I_{JUMP} (= FRAME_INTERVAL of the PLP) is thereby not relevant since it indicates the reoccurrence rate of the PLP and not the extension of one interleaving frame.

Despite of the FEC block count in one TI-block being always an integer, the sub-slices might contain cells from other TI-blocks basically separating a FEC block into two T2 frames [1, p.54-58]. Due to channel switch times and practical reasons such enormous delays exceeding several seconds should be avoided [5, p.38-39] and split FEC block(s) might even be partly omitted by ignoring a part of the stream.

H. Featured MISO, time-frequency slicing

An optional feature is the usage of 'one-way' MISO with either spatial or polarization diversity in DVB-T2. This can lead to problems with signal reconstruction [7] but also enables advantages due to the separate processing of two streams with doubled scattered pilots [5, p.25]. It might also enhance polarimetric measurements as evaluated in [8] in case of

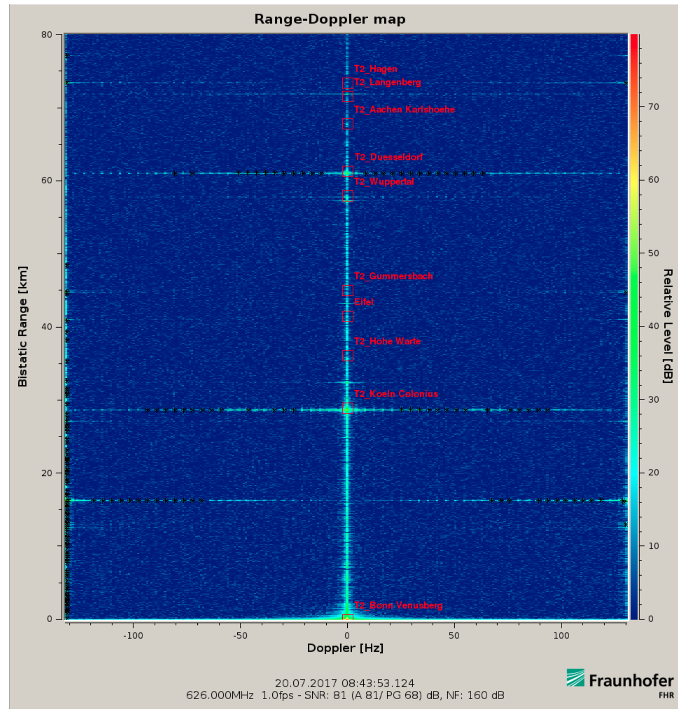


Fig. 3. Resulting range-Doppler map for insufficient channel estimation of a 32k 1/16 GI (PP4) reference signal with multipaths extended close to the guard interval and strong SFN transmitters requiring temporal estimate to fix.

transmit polarization diversity on the same frequency band. By using a more complex receive antenna structure, either MISO or MIMO techniques might be combined with the Alamouti technique [9] to reconstruct the transmitted streams. Due to the lack of measurement data, this situation could not be tested yet.

The time-frequency slicing (TFS) option is the subsequent transmission of PLPs on several RF channels. This technique enables frequency diversity but requires fast retuning of the receivers with less tuners than the number of RF channels [1, p.156]. For TFS usage, the sub-slices of the type 2 PLPs will be spread and contained at the end of a T2 frame [1, p.155]. However, TFS will probably not be used inside Germany [4].

IV. Reciprocal Filtering

A. Description

The reciprocal filter is a method for passive radar processing which has been described in [10], [11]. Basically, it performs a deconvolution of the received signal with the reference signal and it has the advantage of providing low side lobes and a high dynamic range in the presence of a direct signal interference from the transmitter. In order to exploit the orthogonality, the received stream has to be synchronized and evaluated on a per symbol basis (batch processing). The method thereby creates a conjunction between the maximum target range and the unambiguous Doppler interval.

The reciprocal filtering inherently removes ambiguities from e.g. scattered pilots. In contrast, matched filter based processing requires mismatching effort [12, p.327] to do this.

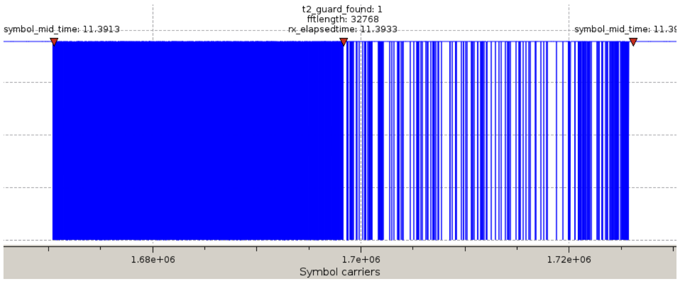


Fig. 4. Sub-carrier gaps after range-compression before interpolation in the frequency domain and the IFFT – left: frame-closing symbol approx. 25 % unoccupied carriers – right: P2 symbol carriers approx. 1 % TR (32k ext)

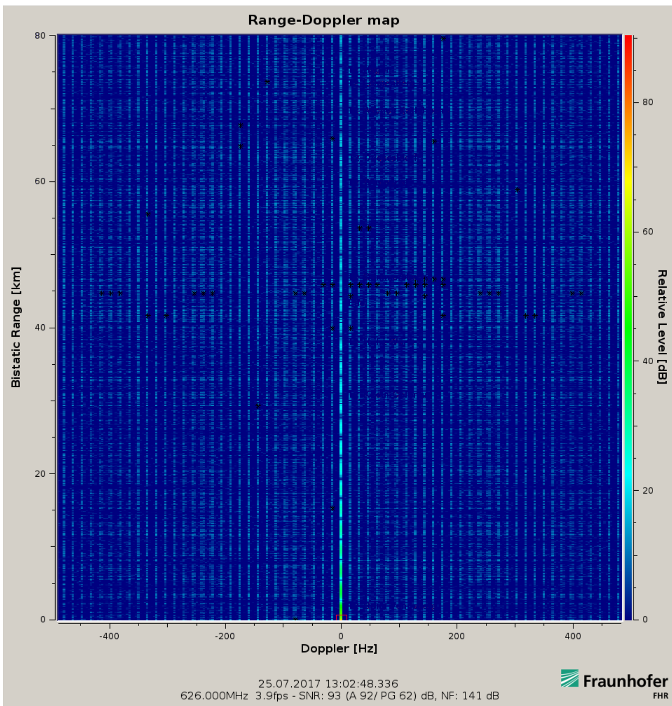


Fig. 5. Resulting range-Doppler map with uncompensated gaps at the end of each T2 frame. The solution is frequency domain interpolation (1 TX).

B. Signal handling of DVB-T2

Despite the signal reconstruction, the usual computation with the reciprocal filter requires equidistant points for the fast Fourier transforms. Therefore, problems may arise in case of mixed T2 frames with various symbol lengths if the coherent processing interval shall exceed one T2 frame duration (max. 250 ms). Even though different modulation schemes are equalized by reciprocal filtering, the resulting C/N will differ for higher order modulations per carrier. The pilot carrier values can still be used for frame, frequency and time synchronization, channel estimation, transmission mode identification and to keep track of the phase noise [1, p.106]. As mentioned before, it might be required to perform temporal inter- or extrapolation for spare pilot patterns, see Fig. 3.

C. Discontinuities in frequency and time

It might be necessary to interpolate the in-band frequency gaps caused by omitting not reconstructible (or zero) PAPR TR and unmodulated carriers in the frame-closing symbol. The illustration in Fig. 4 shows the 27841 active symbol carriers of the frame-closing symbol and of the P2 symbol of the next T2 frame before the IFFT. The interpolation should be applied after the range compression of individual symbols to avoid significant artifacts shown in Fig. 5 in the range-Doppler map.

Another effect is the interruption by the P1 symbol for long integration times. However, the P1 symbol with 224 µs duration in 8 MHz channels has mostly a negligible influence for 16k or respectively 32k symbols in a T2 frame of 250 ms. In case of large dynamic ranges, the discontinuity could be visible in a stockade manner at approximately $-130\,\mathrm{dB}$ of the maximum peak. This dynamic range is usually not achieved in real channels with present noise, thus the integration window is not limited to a single T2 frame and it remains flexible.

D. Unambiguous range and Doppler intervals

The symbols in DVB-T2 networks are mostly transmitted in 16k or 32k mode which means twice or quadruple the useful symbol duration of 8k DVB-T symbols. This will mainly influence the achievable unambiguous Doppler interval. The distance and therefore region with advantageous zero pedestal floor for nonzero Doppler depends on the usage of circular or linear correlation processing and the strength of present targets. In general, it will be extended to the guard interval or useful symbol length whilst the orthogonality is kept [11].

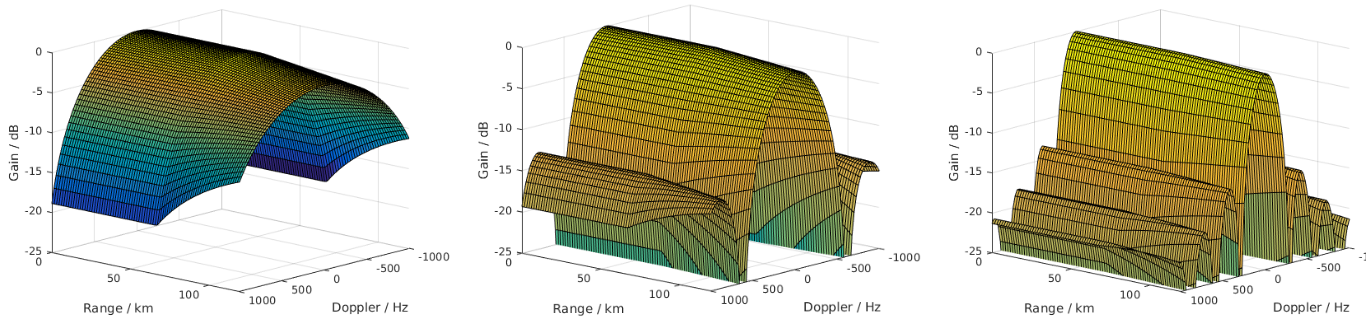
In case of 32k DVB-T2 symbols and 8 MHz channels with an elementary period of $7/64\,\mu\mathrm{s}$, the unambiguous achievable distance can be expressed by either the guard interval duration or the useful symbol duration $T_\mathrm{U} = \mathit{fftlength} \cdot 7/64\,\mu\mathrm{s}$. This puts a limit of 1075 km before aliasing would occur. The main limitation for 32k symbols would be the unambiguous Doppler interval which will be limited to $\pm 121\,\mathrm{Hz}$ assuming a $19/128$ GI-fraction. Under the assumption of carrier frequencies in the UHF band and approximately $1.5\,\mathrm{Hz}$ per $\mathrm{km/h}$, this results in low unambiguously detectable object velocities and might require changes to the processing and/or the target tracking.

E. Doppler processing loss due to the symbol duration

The symbol-wise processing has advantages regarding the computational effort [13, p.303] but it suffers from a loss due to decorrelation within the useful symbol duration with respect to the Doppler frequency f_d. Latter can be expressed as shown in [14, (9)] but it has to be squared to obtain a power factor. The loss will thereby depend on the symbol duration T and the time-of-arrival offset τ. For DVB-T2 with a cyclic-prefix, the bistatic range will influence the magnitude just outside the guard duration α of the cyclic-prefix (FT shift theorem).

$$L_\mathrm{PC} = \left(\frac{1}{\left(1 - \frac{u}{T}\right) \,\mathrm{sinc}\left(\pi\, f_\mathrm{d} \left(T - u\right)\right)} \right)^2 \tag{1}$$

The loss computed in (1) with $u = \max(0, \tau - \alpha)$ is illustrated in Fig. 6 whereby it is noticeable even for low Doppler shifts for increasing symbol lengths and with a (small) range dependency after the guard also for 32k. At just 220 Hz Doppler shift, this might result in an additional loss of 12 dB for 32k, approx. 2 dB for 16k and below 1 dB for 8k symbols in 8 MHz channels just due to the frequency offset.



(a) for 8k symbol with 896 µs and 1/4 GIF (b) for 16k symbol with 1792 µs and 1/8 GIF (c) for 32k symbol with 3584 µs and 1/16 GIF

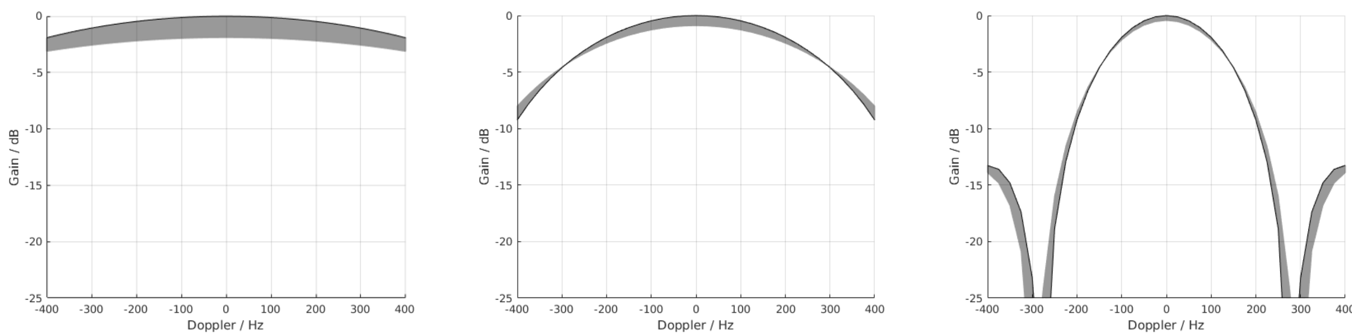


Fig. 6. Simulation results for the Doppler sensitivity evaluation of (1) within a bistatic range from 0 to 120 km and a cyclic prefix of 67.2 km

F. Work-around solutions and compensation

A rotation (cyclic shift) of the FFT matrix of the received signal described in [15] is usually not sufficient to compensate for the limited unambiguous Doppler range without some loss of dynamic range due to the presence of the direct path interference (DPI). Therefore, it is necessary to think of possibilities to either cancel the DPI in advance or modify the processing by the use of another method which does probably not keep the OFDM orthogonality. This consideration has to be carried out with respect to real-time capability and is subject to the available signal configurations and detection demands.

V. Real-time capable implementation

Passive radar processing usually has to deal with signals that are not known a priori. It is therefore necessary to process the signal used for reference signal reconstruction faster than the overall process duration including all delays within this timespan. The multistatic setup was programmed using GNU Radio scheduling and MPI communication between the nodes. The idea of a DVB-T2 demodulator is shown in [5, p.152].

In order to achieve a multistatic real-time capability with a GNU Radio supported (scheduled) implementation, a pre-configuration from prior L1 signaling has been used to enhance the throughput of the adaptive input filtering and reference signal generation. It is thereby needed to balance the overall workload between the per CPU-core scheduled blocks and perform as much as necessary data buffering. The GNU Radio framework provides two methods for inter-block signaling, first data-synchronous 'tags' which can be used to pin information for succeeding blocks and second 'asynchronous messaging' to inform preceding blocks of information from the signaling or post-synchronization. This is e.g. the symbol count in the current T2 frame retrieved from the L1 signaling or information from the post-synchronization block. The digitalized signal is handled in a stream representation to be flexible for individual carrier counts, guard intervals and bandwidths (vs. sampling).

If it was not possible to reconstruct the signal due to time interleaving or a decoding problem, it would be possible to use a noisy reference. However, this would directly impact the detection performance [16] and requires mismatching effort to remove ambiguities. Decoding problems might occur either due to the lack of a particular DVB-T2 feature implementation or simply because of a weak or distorted signal.

VI. Conclusion

The DVB-T2 transmission standard offers a set of features to enhance the waveform flexibility for digital television. If the purpose is passive radar processing exploiting the transmission, several challenges will arise from these dynamically addable features and from their direct limitations on the requirement to achieve a specific evaluation performance.

In particular, the optional power reduction techniques, arbitrary constellation points and time interleaving might lead to challenges for the signal reconstruction but depend on the actual configuration by the service broadcaster. The longer symbol durations planned for DVB-T2 systems compared to DVB-T result in more problems in terms of Doppler sensitivity. However, the reconstruction can be done in real-time if the implementation is flexible enough to treat the used features.

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