



DELIVERABLE 13.1
TIME-FREQUENCY SLICING (TFS)
ANALYSIS, MEASUREMENTS AND
SIMULATIONS

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Deliverable 13.1 – TFS analysis, measurements and simulations

Abstract – Time-Frequency Slicing (TFS) is a novel digital TV wireless transmission technique that consists in transmitting the services across several channels with frequency hopping and time-slicing, breaking the existing paradigm of transmitting TV services in a single RF channel (multiplex). TFS was originally proposed in the standardization process of DVB-T2 (Digital Video Broadcasting – Second Generation Terrestrial), but was finally made an informative part of the standard (not normative) due to the need of implementing two tuners in the receivers. TFS can provide important gains both in terms of capacity due to improved statistical multiplexing (StatMux), and coverage (noise limited as well as interference limited) due to improved frequency diversity. DVB-NGH (Next Generation Handheld) has adopted TFS because it can be operated with a single tuner without adding excessive complexity at the receivers. This report provides an overview of the transmission technique time-frequency slicing, describes its implementation in DVB-NGH, and provides illustrative performance evaluation results about the coverage gain with field measurements and physical layer simulations calibrated within the NGH standardization process. Finally, simulation results showing the possible spectrum-efficiency gains using TFS in interference-limited networks are presented.



Table of Contents

- 1 INTRODUCTION AND BACKGROUND..... 6**
 - 1.1 TFS IN DVB-T2..... 6
 - 1.2 TFS IN DVB-NGH 7
- 2 TIME-FREQUENCY SLICING CONCEPT AND OPERATION MODES 10**
 - 2.1 INTRA-FRAME TFS..... 10
 - 2.2 INTER-FRAME TFS 11
- 3 TFS IMPLEMENTATION IN DVB-NGH 12**
 - 3.1 GATEWAY..... 12
 - Data Scheduling for Intra-Frame TFS..... 12
 - Data Scheduling for Inter-Frame TS..... 14
 - 3.2 MODULATOR..... 15
 - TFS and Rotated Constellations..... 15
 - 3.3 RECEIVER..... 16
 - TFS Frequency Hopping Time..... 16
- 4 TFS CAPACITY GAIN..... 18**
- 5 TFS NETWORK GAIN..... 19**
 - 5.1 COVERAGE GAIN 19
 - Factors resulting in differences in the signal level 20
 - Simplified TFS model..... 24
 - Considerations on the coverage of the multiplexes..... 24
 - 5.2 TFS INTERFERENCE GAIN 25
- 6 SPECTRUM EFFICIENCY INCREASE BY IMPROVED INTERFERENCE PERFORMANCE AND OPTIMIZED NETWORK DESIGN..... 27**
 - 6.1 INTRODUCTION 27
 - Propagation model 28
 - Shadow fading 29
 - Frequency-dependent fading..... 30
 - 6.2 USE CASES 30
 - TFS 30
 - TFS with multiple frequency reuse patterns (MFRP) 31
 - TFS with mixed polarization network (MPN) 32
 - TFS with multiple frequency reuse patterns and mixed polarization network 33
 - 6.3 COMPUTER SIMULATIONS 34
 - Results..... 34
 - 6.4 CONCLUSIONS..... 35
- 7 TFS PERFORMANCE EVALUATION FROM MEASUREMENTS..... 36**
 - 7.1 MEASUREMENT SETTINGS 36
 - 7.2 TFS COVERAGE GAIN DEFINITION 36
 - Simplified Model for the TFS Coverage gain..... 36
 - Analysis of the TFS coverage gain from an Information Theory point of view 37



Deliverable 13.1 – TFS analysis, measurements and simulations

7.3	EVALUATION OF THE TFS GAIN FROM FIELD MEASUREMENTS	39
	Outdoor Measurements	39
	Indoor Measurements	40
	Optimal Spectrum Allocation with TFS	40
8	TFS PERFORMANCE BASED ON PHYSICAL LAYER SIMULATIONS	42
8.1	SIMULATION SETTINGS	42
8.2	RESULTS	43
	Influence of the Code Rate in the TFS Performance	43
	Influence of Rotated Constellations in the TFS Performance	43
9	REFERENCES.....	45
	ANNEX: DETAILED ANALYSIS OF THE TFS GAIN FROM FIELD MEASUREMENTS	47

1 INTRODUCTION AND BACKGROUND

Time-Frequency Slicing (TFS) is a novel transmission technique that consists in transmitting the digital TV services across several Radio Frequency (RF) channels by means of frequency hopping and time-slicing (i.e., discontinuous transmission of each service). TFS breaks the existing paradigm of transmitting TV services in a single RF channel (multiplex), where the reception of a particular service is simply performed by tuning the RF channel which carries the desired service [1]. With TFS, services are sequentially and discontinuously transmitted over a set of several RF channels. Fig. 1 depicts the differences between the transmission of three services in the traditional way (each multiplex in a different RF channel) and using TFS over three RF channels. With TFS the reception of a particular service is performed following dynamically over time the frequency hops among the different RF channels.

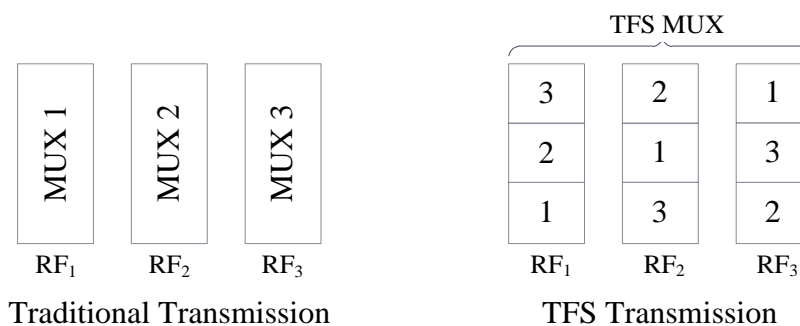


Figure 1. Traditional digital TV transmission (left) and TFS (right) over three RF channels.

The advantages of using TFS for the transmission of TV services can be addressed from two different points of view: a coverage gain due to improved frequency diversity, and a capacity gain due to improved statistical multiplexing (StatMux) for Variable Bit Rate (VBR) services. The frequency diversity provided by TFS can be very significant, since services can be potentially spread over the whole RF frequency band. Furthermore, the combination of multiple RF channels into a single TFS multiplex allows for an almost ideal StatMux gain [2].

TFS was originally proposed within the standardization process of DVB-T2 (Digital Video Broadcasting – Second Generation Terrestrial) [3]. Although it was initially adopted for the baseline, it was finally only specified in the informative part of the T2 specification due to the need of implementing two tuners (front-ends) at the receivers, which would have caused an important increase in receiver complexity and implementation cost. The next generation mobile broadcasting standard DVB-NGH (Next Generation Handheld) has adopted TFS because it can be operated with a single tuner without adding excessive complexity at the receivers.

1.1 TFS in DVB-T2

The main driving force for DVB-T2 was to increase the spectral efficiency of digital terrestrial TV (DTT) networks for the transmission of HDTV services. TFS was originally proposed by the Swedish broadcast network operator Teracom in order to increase the efficiency of the statistical multiplexing of high quality TV services and to improve coverage due to increased frequency diversity. Although DVB-T2 provides a

significant capacity increase over its predecessor DVB-T (Terrestrial), in the order of 50% up to 70% [4], the number of HDTV services that can be allocated per multiplex is limited. Hence, it is not possible to exploit the maximum StatMux gain. The main idea behind TFS was to combine the capacity of several RF channels (up to six) to create a high-capacity multiplex that would allow for an almost ideal StatMux gain [5]. But TFS was also proved to provide an important gain in terms of coverage due to enhanced frequency diversity. Large-scale field measurements performed during the T2 standardization process by Teracom reported gains in the order of 4 to 5 dB with four RF channels for both fixed roof-top and portable reception [2]. The TFS coverage gain was expressed as the difference between the average signal strength and the minimum signal strength calculated over all RF frequencies in each location. It should be noted that this coverage gain can be turned into a capacity gain, since it would be possible to use a transmission mode with a higher spectral efficiency keeping the same coverage. Furthermore, this gain is independent of the gain due to improved statistical multiplexing, so the two gains will add (i.e., gain factors can be multiplied).

Although not evaluated in the T2 standardization process, it was acknowledged that TFS can also improve the transmission robustness against channel time variations and the tolerance against static and time varying interferences, since interference level usually varies with frequency. Thanks to the frequency interleaving across several RF channels, depending on the error correction capability of the Forward Error Correction (FEC) scheme, one, or even several, of the RF signals could be completely lost provided that the other RF signals are good enough.

The major disadvantage of TFS in DVB-T2 is the requirement of two tuners at the receivers to receive a single service, which makes the receivers more complex and expensive. It was not always possible to guarantee a time interval between successive frames of the same service long enough for frequency hopping among RF channels with a single tuner. However, internally in a frame a single tuner would have been sufficient. Hence, the technique was finally moved from the normative part of the T2 specification, and was left as an informative annex, although specified in detail, for future implementations [3]. Full support for TFS can be also found in surrounding specifications such as PSI/SI (e.g., the T2 delivery system descriptor includes a field for TFS) [6], and the interface between the gateway and the modulators known as T2-MI [7].

1.2 TFS in DVB-NGH

The implementation of TFS in NGH was part of two Call for Technologies responses submitted by Teracom, oriented to a reuse of the T2 specification, and Sony and the Technical University of Braunschweig, oriented to an adaptation of DVB-C2 (2nd generation Cable) specification.

The Sony/TUBS proposal concerning TFS [8] is based on Data Slicing concept (implemented in DVB-C2) that consists of dividing a wide transmission bandwidth of a RF channel (e.g. 8 MHz) in the frequency domain into narrower Data Slices (sub-bands) with a maximum bandwidth of 1.7 MHz. Hence, the receiver only needs to decode a single Data Slice out of the overall transmitted bandwidth which provides the system a very low power consumption on receiver side as segmentation in N bands of the overall channel bandwidth allows the receiver tuner to operate 1/N of the bandwidth and at N times slower rate.

Data-Slicing was rejected as a T2-like frame structure achieves better performance in most of the possible NGH scenarios and Data Slice bandwidth (1.7 MHz) is not enough to achieve bit rates higher than 1Mbps at reasonable spectral efficiencies.

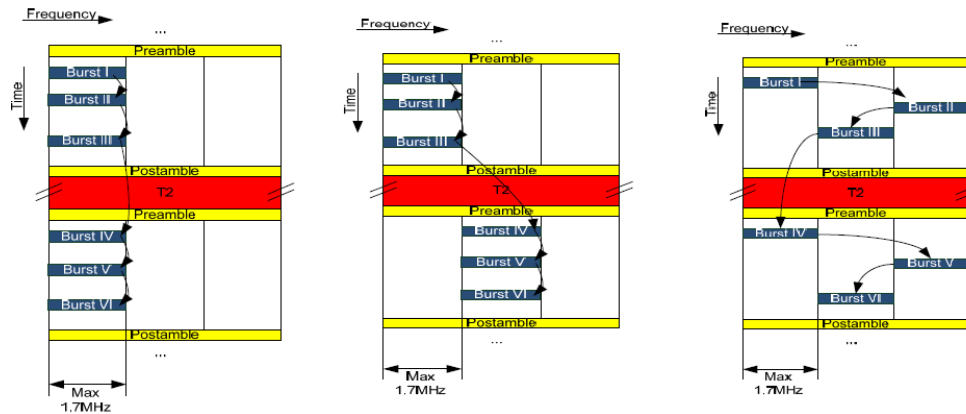


Figure 2. Operation modes of the Sony/TUBS Data-Slicing proposal

In a similar way as for DVB-T2, Teracom considered that TFS could also be very beneficial for DVB-NGH, offering both a gain in capacity due to more efficient StatMux and a gain in coverage due to increased frequency diversity. However, the point of view from which TFS has been addressed in DVB-NGH is slightly different from that of DVB-T2. For DVB-NGH it is considered as a likely scenario that NGH services are introduced within one or more existing T2 multiplexes by the FEF (Future Extension Frame) mechanism [9]. On each RF channel there would therefore be a time division between the T2 signal and the NGH signal. For an NGH receiver the T2 frame (which does not have to be received) would provide a natural guard period allowing the receiver to perform frequency hopping at frame boundaries. Furthermore, in contrast to DVB-T2, where the focus was on HDTV services with very high bit rate, in DVB-NGH the maximum coded service data rate (i.e. including source and parity data) has been limited to 12 Mbit/s to reduce the complexity of the receivers. Such limitation relaxes the time constraints to correctly follow the frequency variations of the transmitted TFS signal, and allows, together with the above-mentioned guard period between NGH frames, the use of receivers with a single tuner.

The main issues that prevail in mobile broadcasting are related to improvements in coverage to cope with the more severe propagation conditions and reduce the network infrastructure investments, and improvements in the power consumption of the receivers to increase the battery life. Hence, whereas the main driver for DVB-T2 was increased capacity, the main goal of DVB-NGH is improved coverage, especially for pedestrian indoor reception [9].

The benefits of TFS in terms of coverage in DVB-NGH go beyond those identified in the DVB-T2 standardization, where fixed reception was the most important reception case. TFS can provide not only a significant coverage gain, but also improve the robustness of the transmitted signal. The additional frequency diversity is especially important for pedestrian reception conditions, where the time diversity is very little or inexistent. Moreover, for mobile reception the increased frequency diversity can reduce the requirements for time interleaving, reducing the end-to-end latency and zapping time. This applies to fixed as well as portable and mobile reception.



Deliverable 13.1 – TFS analysis, measurements and simulations

Another important difference in TFS operation is that it is not feasible to implement TFS frequency hopping within a frame (i.e., intra-frame TFS) when using fairly short FEFs to transmit NGH services. The frequency hopping is then instead done across frames (i.e., inter-frame TFS). Inter-frame TFS does not allow to exploit statistical multiplexing in the same way as intra-frame TFS, because the total multiplex capacity is limited to that of one RF channel (although hopping), whereas with intra-frame TFS several RF channels are used simultaneously for TFS. However, it maintains the coverage gain due to combined frequency and time diversity.

Another important benefit of TFS is the possibility to find spectrum for DVB-NGH services more easily and in a more flexible way, since it is possible to combine several RF channels with different percentages of utilization allocated to DVB-NGH thanks to the new FEF bundling mechanism defined in DVB-NGH.

TFS has been included in the sheer terrestrial SISO/MISO (Single Input Single Output/ Multiple Input Single Output) Base profile of DVB-NGH as well as in the MIMO (Multiple Input Multiple Output) profile of DVB-NGH. The maximum MIMO performance is achieved when both horizontal (H) and vertical (V) polarization signals are received with the same power. However, for a given RF channel the frequency and directional variations of the H and V antenna diagrams can be highly different, and there can therefore be large variations already in the transmitted signal. TFS can smooth the negative effects of such variations, since the difference varies with the frequency.

2 TIME-FREQUENCY SLICING CONCEPT AND OPERATION MODES

TFS can be implemented within the same frame (intra-frame TFS), by means of frequency hopping between the sub-slices of one frame¹ which are transmitted in different RF channels, and frame-by-frame (inter-frame TFS), using frequency hopping only at frame boundaries. The implementation of one or the other depends on the availability of capacity for DVB-NGH on the different RF channels, the type of the PLP (Physical Layer Pipe), and the frame length. The use of TFS is linked to the PLP concept introduced in DVB-T2. A PLP is a logical channel at the physical layer that may carry one or multiple services, or service components [4]. Each PLP can have a unique bit rate (including variable bit rate) and error protection parameters (modulation, code rate, and time interleaving configuration, MODCODTI). PLPs of Type 1 are transmitted in a single burst (slice) within the logical frames. PLPs of Type 2 are transmitted in at least two sub-slices within each logical frame and with at least one subslice per RF channel. Both types of PLPs allow multi-frame time interleaving over several frames.

2.1 Intra-frame TFS

For intra-frame TFS, frequency hopping is performed within a frame, between the sub-slices of the desired PLP/PLPs, as depicted in Fig. 3. The sub-slices of one PLP are uniformly distributed among the set of RF channels of the TFS multiplex. The number of sub-slices must be a multiple of the number of RF channels. It should be noted that the different RF channels must be synchronized such that the receivers can perform frequency hopping between sub-slices. This mode of operation allows for intra-frame and inter-frame time interleaving. With intra-frame time interleaving, all sub-slices of one PLP within one frame are jointly interleaved in frequency and time, thus increasing frequency and time diversity. When inter-frame interleaving is used, the FEC blocks of each PLP are convolutionally interleaved over several frames prior to this. Intra-frame TFS allows to exploit both increased frequency and time diversity as well as enhanced statistical multiplexing.

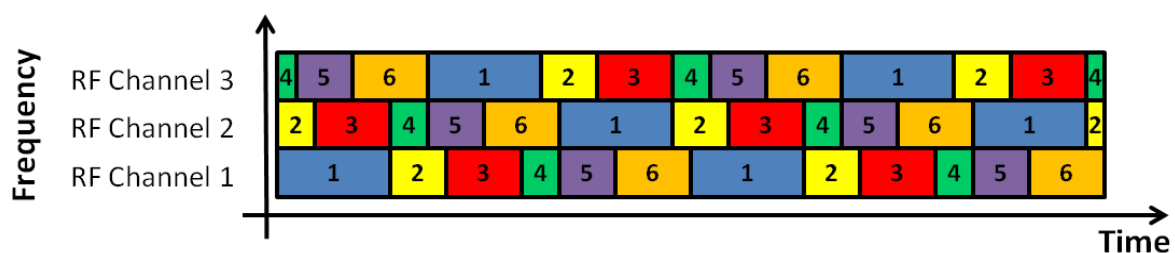


Figure 3. Example of intra-frame TFS with 6 PLPs and 3 RF channels (with a total number of 6 sub-slices).

Intra-frame TFS is suited for long NGH frames (e.g., 150-250 ms, 250 ms being the maximum frame size for both DVB-T2 and DVB-NGH), as it is may not be possible to guarantee a correct frequency hopping among RF channels within shorter frames with a single tuner. However, this mode of operation also depends on the number of RF channels, the number of sub-slices, the MODCOD and peak rate for the PLP. For example, the lower the MODCOD and the higher the selected peak bit rate, the larger will the total amount of cells be in

¹ In this case a logical frame fits exactly into one frame (logical channel type D)

the frame for the PLP. Increasing the number of RF channels also leads to lowering the time interval for frequency hopping.

2.2 Inter-frame TFS

With inter-frame TFS, each frame is transmitted in a different RF channel, and frequency hopping is performed on a frame basis, see Fig. 4. Inter-frame TFS can be used for both Type 1 and Type 2 PLPs. It is the only TFS operation mode possible for short frames and Type 1 PLPs. Inter-frame TFS requires inter-frame time interleaving in order to jointly exploit the time and frequency diversity. It can exploit a somewhat longer time interleaving durations than intra-frame TFS, but the drawback is that it is not possible to improve the efficiency of the statistical multiplexing. On the other hand, the time constraints between frames are usually more relaxed.

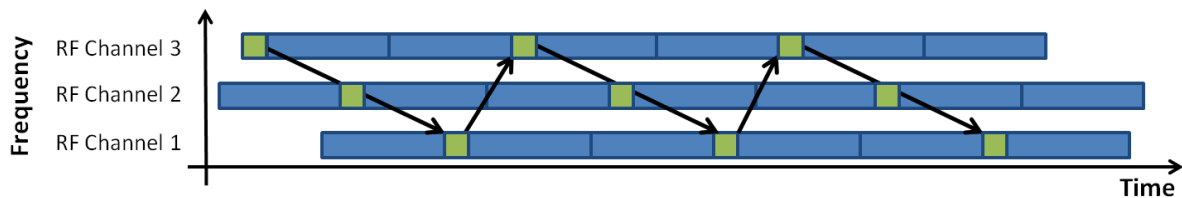


Figure 4. Example of inter-frame TFS transmission with DVB-NGH services in future extension frames (FEFs) of DVB-T2 over 3 RF channels.

3 TFS IMPLEMENTATION IN DVB-NGH

3.1 Gateway

On the network side, the NGH gateway should assure that receivers can follow the TFS transmission with a single tuner. A correct scheduling of the data from each PLP is also necessary in order to exploit the combined frequency and time diversity. Ideally, a FEC codeword should be uniformly distributed among all RF channels and properly spread in time.

However, time diversity is tightly linked to zapping time. Zapping time involves the inevitable delay produced when a user receiving a particular audio/video service decides to switch to a different service carried on another stream as the new service cannot be presented immediately to the user, unless the receiver performs decoding in parallel of both services (e.g. if they are both transmitted in the same PLP). The main factor that involves zapping time performance is the interleaving depth. With TFS, interleaving depth is typically equal to the TFS cycle time (the time interval between the reception of two consecutive data bursts in the same RF channel) or a multiple thereof. For intra-frame TFS (without using convolutional interleaving), the average zapping time, when zapping from another PLP of the same NGH signal, is 1.5 times the frame time which corresponds to the time needed to receive the start of the frame (in average 0.5 frame) and the time before data can be reproduced (1 frame, in order to read the signaling parameters and to receive the time-interleaved data cells contained in the frame). Hence, zapping time for intra-frame TFS is only related to frame time. For inter-frame TFS it mainly depends on the time interleaving depth (the number of frames over which a FEC codeword is spread).

Data Scheduling for Intra-Frame TFS

For intra-frame TFS, the NGH specification defines a deterministic scheduling process which ensures the necessary time interval between sub-slices for sequential reception with a single tuner. The algorithm leads to a regular distance between sub-slices with a constant hopping time between slots. An illustrative example is depicted in Fig. 5. The starting point is a set of consecutive data cells from the different PLPs that are going to be transmitted (in the example, there is a total of 6 PLPs). The total number of PLP cells is, then, divided into the number of sub-slices to be transmitted in each RF channel (2 sub-slices per RF channel in our example). The previous division establishes the so-called *SubsliceInterval*, which is the time interval (or the number of cells) between two data bursts of the same PLP in an RF channel:

$$SubsliceInterval = \frac{n_{Cells}}{n_{Subslices}}, \quad (1)$$

$$RF_{Shift,i} = i \cdot \frac{SubsliceInterval}{n_{RF}} \quad (i = 0, 1, \dots, n_{RF}-1), \quad (2)$$

where n_{RF} is the number of RF channels and n is defined from 0 to $n_{RF} - 1$.

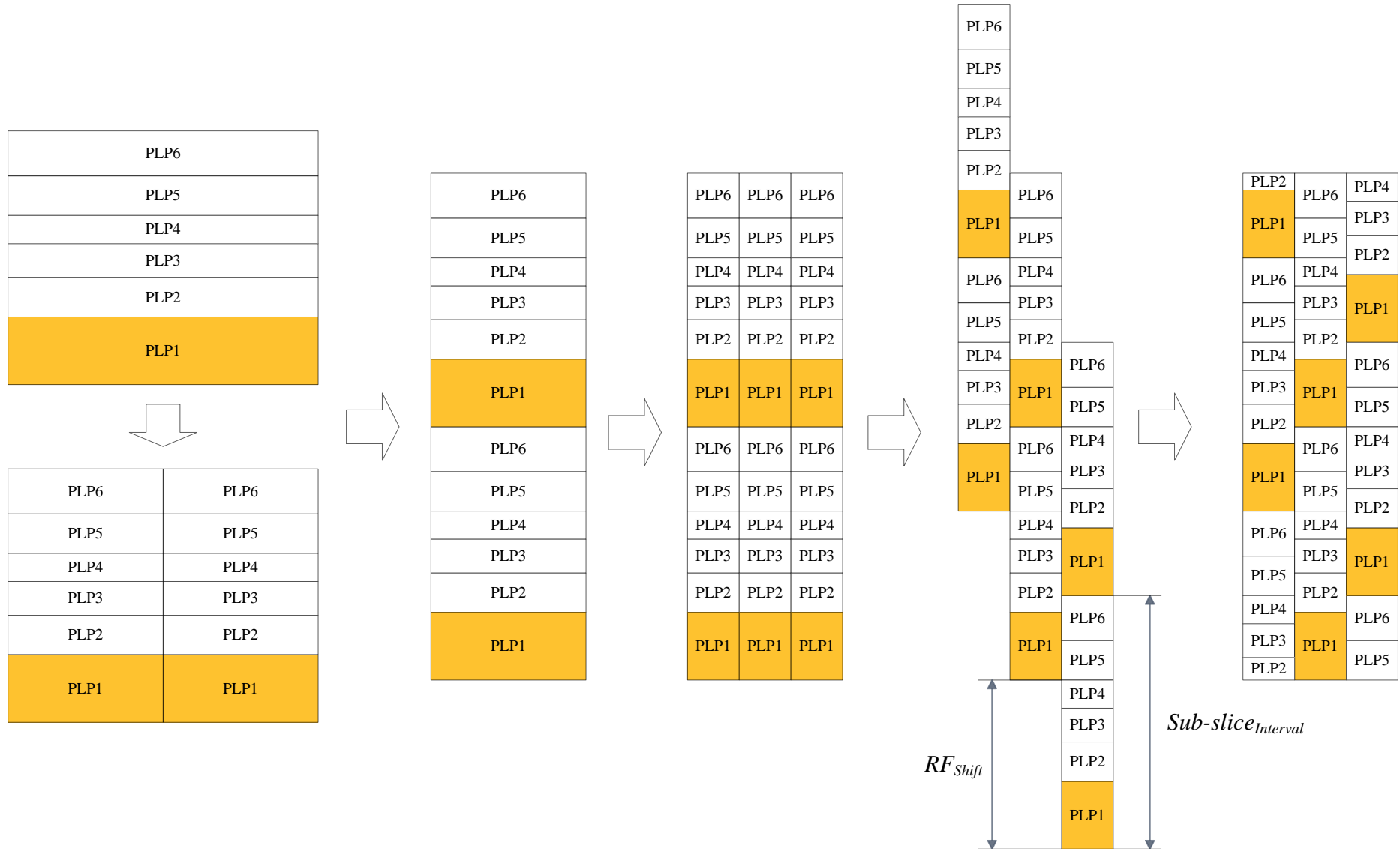


Figure 5. Scheduling of the data PLPs at the gateway for intra-frame TFS. Example for 6 PLPs, 3 RF channels, and 6 sub-slices.

The final folding of the cells that exceed the last sub-slice (of the last PLP) of the RF channel which has not been shifted leads to a frame structure in which all PLPs are regularly spaced with time for frequency hopping. It should be noted that the previous process defines the scheduling; however, scheduled cells have not yet been filled with the data of the services. Only positions in the frame have been defined. Time interleaved PLP cells are introduced into sub-slices in the natural time sequence, independently of RF channel. The first time interleaved cell is, therefore, introduced in the first cell position of the first sub-slice of the PLP (independently of the RF channel in which it appears).

A proper scheduling for intra-frame TFS guarantees frequency hopping internally in a frame with a single tuner. However, a guard period is needed to allow enough tuning time between the last PLP sub-slice in one frame and the first PLP sub-slice in the following frame, see Fig. 6. The guard period can be achieved either by the use of a FEF part between the frames or by the use of Type 1 PLPs for a long enough time period to allow the frequency hopping.

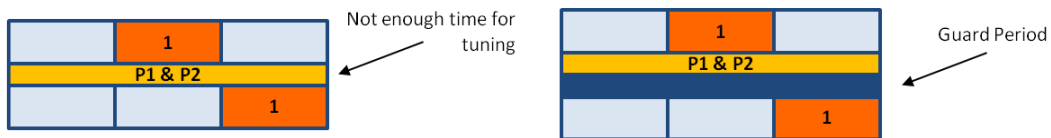


Figure 6. Guard interval insertion between data slots.

Data Scheduling for Inter-Frame TS

Inter-frame TFS operation within the FEFs of a T2 signal relaxes data scheduling since frequency hopping is not performed inside a frame, having longer time intervals between data bursts. Although timing is less critical for inter-frame TFS, a trade-off between the convenient time interleaving and zapping time must be reached for inter-frame TFS operation. For regularly-spaced and time shifted (see right part of Fig. 7) T2 FEFs an inter-frame TFS scheduling must meet the following equation:

$$N \cdot (FEF_{length} + Gap_{length}) = FEF_{length} + k \cdot T_{frame}, \quad (3)$$

where N is the number of interleaved T2 FEFs, FEF_{length} is the length of a T2 FEF, Gap_{length} is the gap between adjacent T2 FEFs (but on different frequencies), and T_{Frame} is the length of the T2 frame and k is the number of T2 frames between T2 FEFs. This equation defines the TFS cycle time for inter-frame TFS which mainly depends on the spacing among FEFs and the number of FEFs throughout data is spread. In general, zapping time increases with the spacing among FEFs. However, large spaced FEFs increase time interleaving on the channel which also increases time diversity. The different schemes presented in Fig. 7 deals with this issue.

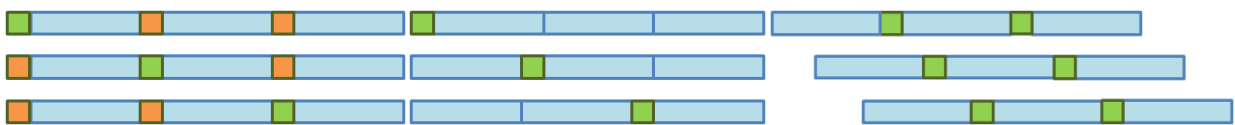


Figure 7. Interleaving over FEFs with frequency hopping between RF channels using co-timed T2 frames, time shifted FEFs but co-timed super frames, and time-shifted super frames.

Although the first two schemes provide the best performance for frequency and time diversity, they provide long zapping times. To guarantee the possibility of using long interleaving without seriously affecting

zapping time, it is proposed the use of time-shifted super frames. With all options, some synchronization needs to be implemented in the TFS multiplex among the different RF channels.

3.2 Modulator

The basic modulator block diagram of a NGH transmitter is depicted in Fig. 8. It includes several OFDM generation chains, one for each RF channel of the TFS multiplex. The most important blocks involved in the TFS operation are the frame mapper and, when using rotated constellations, the component interleaver. The frame mapper allocates the interleaved NGH services in their corresponding frame according to the TFS configuration parameters. The component interleaver ensures that the dimensions of each constellation point are transmitted over all possible combinations of RF channels and increases the frequency diversity as much as possible. In this case, the relevant parameters are the number of RF channels and the number of TFS cycles over which a FEC block is time interleaved.

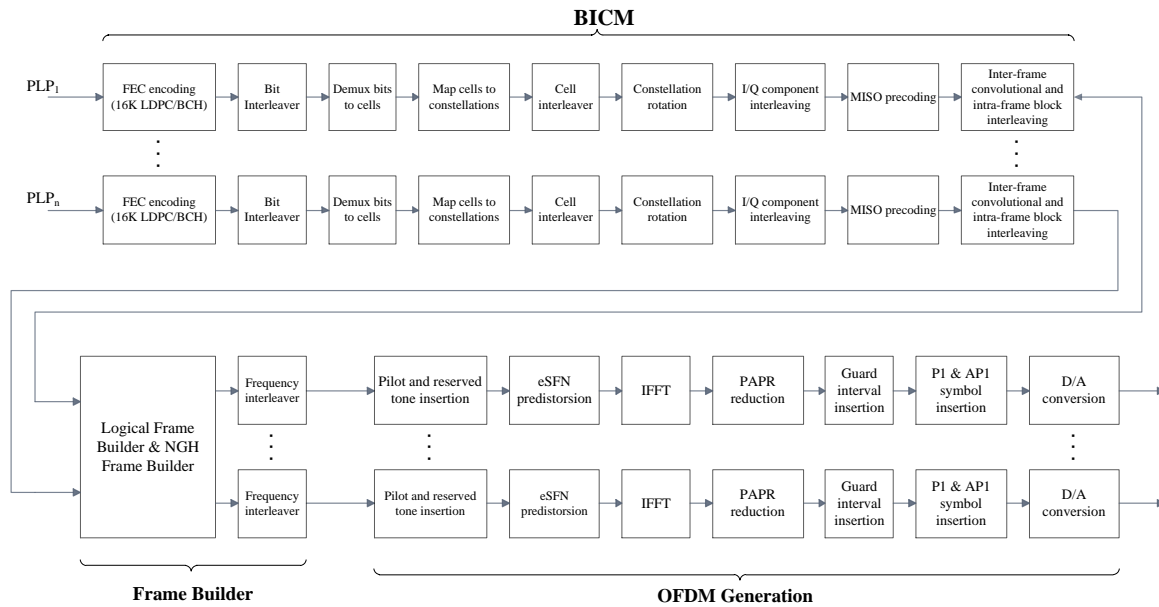


Figure 8. DVB-NGH modulator block diagram with TFS.

TFS and Rotated Constellations

With conventional non-rotated constellations, the in-phase (I) and quadrature (Q) components of one constellation symbol are transmitted in a single cell at a given time and frequency (carrier). Hence, the loss of the cell implies the complete loss of the constellation symbol. Rotating the constellation in the complex plane with an appropriate angle, each transmitted component (I and Q) contains enough information by itself to allow the receiver to know which symbol was transmitted. Thus, if one of the components is lost (e.g., affected by a deep selective fading of the channel), the other can be used to recover the complete symbol. To be able to exploit this additional gain for TFS, the I and Q components of each cell should be transmitted in different RF channels, since these may have a very different fading. In DVB-T2, a cyclic delay is applied to the Q component after the constellation rotation, such that the I and Q components of each symbol are transmitted in consecutive cells. Then, a cell interleaver is applied to randomize the position of each component within the FEC frame. After time interleaving, I and Q of the same original cell appear in quasi-random positions in the T2 frame. This implies that I and Q sometimes appear in the same RF channel, which is undesirable. With e.g. 2 RF channels, every second I component has its original Q component in the

same RF channel [1]. In DVB-NGH, a new component interleaver has been introduced to guarantee that the transmission of the component of the same symbol does not occur on the same RF channels.



Figure 9. QPSK non-rotated constellation (left) and QPSK rotated constellation (right).

3.3 Receiver

The implementation of TFS at the receiver is one of the most challenging issues on TFS implementation since receivers need to perform frequency hopping between two RF channels with a single tuner.

TFS Frequency Hopping Time

The NGH specification includes a receiver model for frequency hopping. Only those transmission modes that are receivable with receivers following this model are allowed. The receiver is assumed to have a tuning time, T_{tuning} , that is 5 ms or lower. The minimum frequency hopping time between two data slots, T_{FH} , can be calculated as:

$$T_{FH} = 2 \cdot T_{ChE} + T_{tuning}, \quad (4)$$

where T_{ChE} is the time required for fine frequency synchronization and channel estimation, and **Fel! Hittar inte referensskälla.** T_{tuning} is the PLL (Phase Locked Loop) and AGC (Automatic Gain Control) tuning. Fig. 10 depicts this timing.

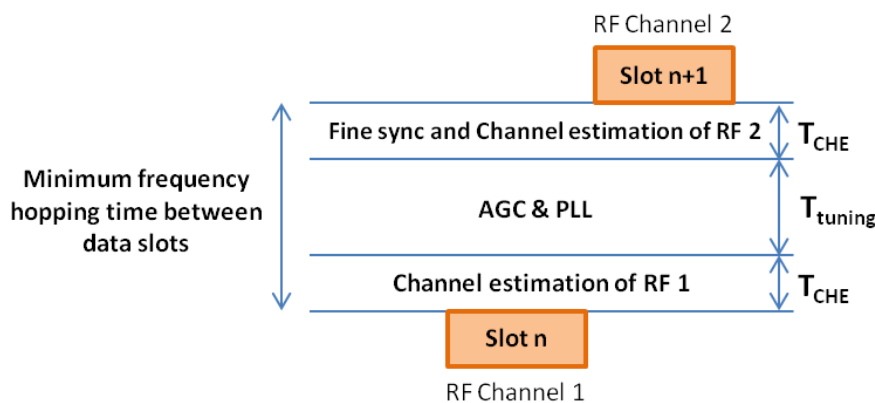


Figure 10. Minimum frequency hopping time between data slots.

In the T2 standardization process, it was acknowledged that a skilful design of the PLL and AGC would require only 5 ms, and since then receiver manufacturers have reported that even lower values are in fact possible. The time gap between the same PLP on two different RF channels does however need to be

somewhat larger than 5 ms because the channel estimation process has to be performed before starting to receive any data slot in the new RF channel, but also there should be some extra time in order to finish the channel estimation in the current RF channel before hopping. T_{ChE} depends on the FFT size, the OFDM guard interval (GI), and the pilot pattern. For example, for a typical mobile configuration for the UHF band with FFT 8K GI=1/4² with pilot pattern PP1 (which requires time interpolation involving three future and past OFDM symbols), the required time gap is increased to 12 ms (eleven symbols). For FFT 16K² GI=1/4 with pilot pattern PP2, which requires time interpolation over one future and past symbol, the time gap is about 11 ms (five symbols).

Table 1. Values for tuning time between slots (in symbols and time) calculated for DVB-T2 transmission modes.

FFT	max GI	T_U (ms)	5 ms as symbols	Part 1 5 ms round up	Part 2 sync & Est before slot	Part 3 estimation after slot	Tuning time between slots	Tuning time between slots (ms)
32K	1/8	3.584	1.24	2	0	0	2	8.06
16K	1/4	1.792	2.23	3	1	1	5	11.20
8K	5/16	0.896	4.25	5	3	3	11	12.94
4K	5/16	0.448	8.50	9	3	3	15	8.82
2K	5/16	0.224	17.01	18	3	3	24	7.06
1K	5/16	0.112	34.01	35	3	3	41	6.03

² Maximum symbol duration with GI=1/4 is 1.12 ms for 8K and 2.24 ms for 16K.

4 TFS CAPACITY GAIN

TFS can provide a capacity gain due to a more efficient StatMux [2], [5]. StatMux exploits the fact that video codecs produce streams of variable bit rate depending on the encoded content. Without StatMux, the capacity of a multiplex should be divided among the different services in a fixed way. This implies a Constant Bit Rate (CBR) video encoding, which does not guarantee an optimum bandwidth usage. StatMux takes advantage of the fact that, statistically, and for a given video quality level, the instantaneous overall peak bit rate of all video streams together is significantly lower than the sum of the peak bit rates of each individual video stream, assuming a central control unit that dynamically allocates capacity to each service while trying to keep the quality of all services constant and potentially the same. Fig. 11 illustrates the difference between CBR encoding and VBR encoding with StatMux.

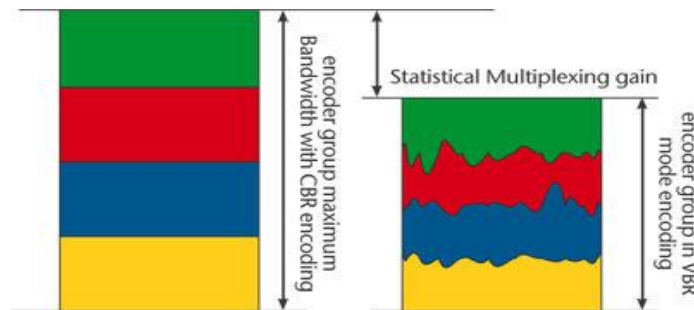


Figure 11. Constant bit rate (CBR) encoding vs. Variable bit rate (VBR) encoding with statistical multiplexing (StatMux).

The so-called StatMux gain is defined as the percentage reduction of the required bit rate compared to CBR encoding for a given quality. The StatMux gain depends on the number of services jointly encoded and multiplexed. Obviously, there is no gain for a single service, but the gain increases asymptotically as a function of the number of services until there is a point where it saturates. For example, in DVB-T2, the maximum StatMux gain for HDTV is reached when multiplexing 18 to 24 programs, in which case the StatMux gain is about 32% [2], corresponding to a (virtual) capacity gain of 47% ($1/(1-0.32) = 1.47$). In NGH the capacity per multiplex is expected in general to be significantly lower than in DVB-T2, but also the bit rate per service may be correspondingly lower, resulting in approximately the same number of services and a similar StatMux gain. Using e.g. an NGH configuration with 10 Mbit/s and 20 services the bit rate per service becomes about 500 kbit/s, which may be adequate for a mobile service. It should be noted however that whereas the above T2 figures are derived using the MPEG-4/AVC coding standard the emerging HEVC standard is a likely candidate for coding with NGH and the StatMux properties of HEVC are not yet known.

5 TFS NETWORK GAIN

TFS may provide a so-called network gain by means of increased frequency diversity. Frequency diversity is the result of the implementation of frequency hopping in the transmitter. This mode of operation leads to transmitting time-slices (bursts) of the same service over different RF channels. Propagation characteristics of the scenario and also network interference may affect the bursts in a different way according to the frequency. At the receiver, the bursts that belong to the same service are recovered and, consequently, each one may result in a different signal-to-noise ratio (SNR). With this, TFS can provide gain advantage to static reception and also improve robustness against channel time variations and interferences.

5.1 Coverage Gain

TFS provides a coverage gain due to increased frequency diversity. In general, the signal of each RF channel is affected by different propagation conditions that cause imbalances in the received strength at each location although the same effective radiated power (ERP) is transmitted in all channels [10]. The imbalances depend not only on the characteristics of the particular propagation scenario, but also on the frequency dependent behavior of some physical elements of the transmission chain (e.g., antenna radiation patterns and ground echo), and the presence of interferences from other networks.

In a traditional DTT network, the perceived coverage of a set of services at a given location is determined by the channel with the worst signal level in each location. Receiving this worst channel assures correct reception of all the multiplexes, which is a natural commercial requirement. With TFS, on the contrary, the coverage is more likely to be determined by the average signal strength among all RF channels used by the TFS transmission. Fig. 12 shows an illustrative example of the effect in the coverage of using TFS in a DTT network with three different RF channels. It should be noted that TFS enlarges the area where all services are correctly received, but reduces the area where at least one service is received (that corresponds to the RF channel with the best signal level). It should however be noted that commercially, when competing digital TV delivery media exist, a missing multiplex is likely to make the user unsatisfied with the DTT service and may trigger a move to alternative delivery media.

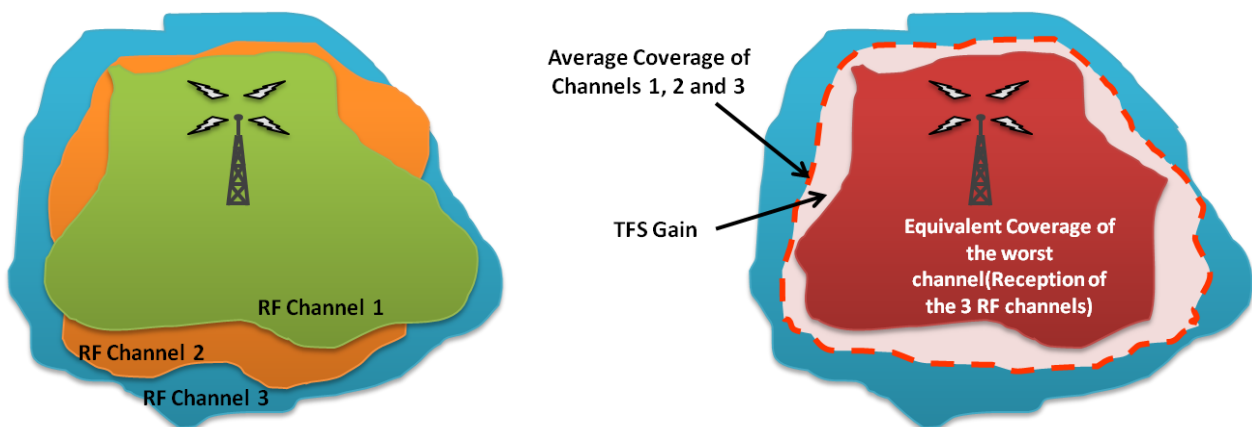


Figure 12. Example of area coverage for three RF channels in a DTT network without TFS (left) and with TFS (right).

The TFS coverage depends on the number of RF channels involved in the transmission and the frequency spacing among them. In general, the gain increases with the number of RF channels and the frequency spacing. The potential gain is very high because with appropriate coding and interleaving even a fully lost RF channel may still allow correct reception of all services. This is similar to the situation with conventional COFDM where a 0 dB echo may totally cancel e.g. every 4th OFDM carrier, but reception only be slightly degraded by this (a few dBs of C/N loss). What matters in both cases for reception is the “global” quality and not so much the quality of a particular RF channel (or OFDM carrier). When there are large variations in signal strength between different RF signals the “good” RF channels tend to compensate for the bad ones. Rotated Constellations (RC) [11] can further improve the performance of TFS by means of increasing diversity [1].

Factors resulting in differences in the signal level

TFS coverage gain is obtained due to differences in the signal strength of the RF channels involved in the transmission. These imbalances in received signal are caused by effects that depend on the deployment scenario and the characteristics of reception. Requirements for digital terrestrial television transmission to fixed, portable, or mobile users are different according to these effects.

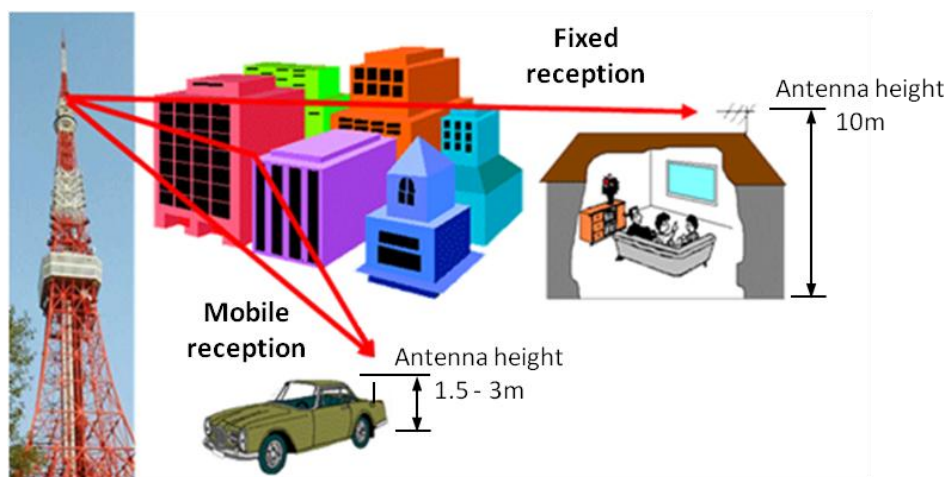


Figure 13. Reception conditions for Fixed and Mobile scenarios

Fixed reception mode is characterized by the use of antennas that are usually placed outdoor on the rooftop. Fixed antennas are mounted in high masts (usually 10 m above the ground level) and pointed towards the transmitting station. These kinds of antennas are usually large and may have directional patterns with suitable gain in order to receive the main contribution from station. The RF channel conditions assume that there exists a path of signal with LOS (line-of-sight) to the transmitter so that the received signal is not mainly affected by reflections or multipath contributions.

Mobile reception is usually associated to pedestrian or vehicular reception at a given speed. In these cases antennas are placed both outdoor and indoor and located at ground level as reception is intended to be made by handheld receivers (for planning issues antenna height is usually taken as 1.5 m above ground). Antenna designs for these kinds of devices differ substantially from static antennas due to restrictions in dimensions and shape as antennas have to be integrated inside them. Moreover, antenna patterns may be omnidirectional with low gain as it is not possible to point the antenna towards the transmitter station. When the receiver



Deliverable 13.1 – TFS analysis, measurements and simulations

moves, reception depends on the speed of the user, the nature of the signal paths and the number of signal reflections. It is assumed that due to the scenario and antenna height reception may be NLOS (non line-of-sight). In general, receivers which are able to provide mobile DTT services must be able to handle very high speeds, strong reflections, fast fading conditions and also shadowing effects due to the presence of non static obstacles when receivers move along a route.

Portable reception is a particular case of mobile reception in which the antenna speed is zero and is usually made in indoor scenarios. In this case the antenna is usually indoor (located at ground level) with poor directionality and low gain. Signal suffer from high attenuation due to the buildings and objects that cause reflections in the signal path and penetration loss produced in walls and roofs in indoor reception.

Some studies were done during the standardization process of DVB-T2 to analyze the performance of the elements in the transmission chain that could cause relevant signal level differences between multiplexes at a particular coverage area. Analysis was done for static reception; however some of them can be applied to other reception conditions. In general, these factors are related to dependences in frequency of the transmitter site, the receiver conditions and the channel through signal is propagated. Some of the elements that were proved to cause differences in signal level are the transmitter antenna diagram, wave propagation, the position of the receiving antenna, the physical and electrical characteristics of the antenna itself and the time variations of signal strength.

The first source in the transmission chain for large differences in received signal strength is the frequency dependence of antenna radiation diagram on the transmitter stations. Antenna is designed to work over the UHF band (in the range from 470 MHz to 862 MHz). This large band implies a compromise between bandwidth and smoothness of the horizontal antenna diagram as it must work properly in almost an octave of frequency.

Most of the main stations have nominally, in the horizontal plane, omni-directional antenna diagrams, however, in practice, the antenna diagrams differ far from the ideal ones. Even a good antenna has variations in gain in the order of 3-6 dB. Moreover, antenna diagram also depend on azimuth. In addition to the normal variations in the horizontal diagram there may sometimes be very large notches, in the order of 10-15 dB, for a certain direction and frequency, as a result of anomalies in the antenna. Fig. 14 shows the antenna diagram for four different frequencies where variation of approximately 6 dB can be observed among frequencies. Variation in antenna diagram can be measured by the portion of degrees in 360 for which two frequencies have differences larger than 3 dB. In general this value is around 25%.

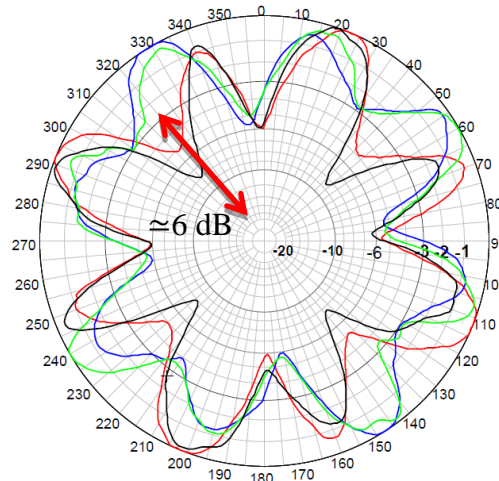


Figure 14. Transmitter antenna diagram measured for 4 different frequencies (different colours in diagram).

The performance of receiving antennas depends on their characteristics and design. For fixed reception, directional antennas are normally used. This kind of antennas are disposed at rooftops and pointed towards the most important signal contribution coming from the transmitter. With mobile reception, antennas are different as they have to be designed to be integrated in handheld devices. Moreover, reception conditions are also different as DTT signals may be received at street level in presence of multiple obstacles and generally without line-of-sight to the transmitter. This leads to the necessity of implementing omnidirectional antennas in the receivers. Leaving aside these changes in design, performance of receiving antennas differs substantially from theoretical approaches. Antenna gain shows large variations as a function of frequency. For planning purposes it is not possible to take into account these large variations. A reference antenna is used instead, leading, in practice, to differences in coverage.

The reference receiver antenna gain (G) is constant over the UHF band. However, the received power at receiver input depends on frequency (f). Therefore, the received power (P) is a function of the field strength (E), antenna gain (G) and the square of the frequency (f^2). Received power (in dB) can be calculated using the following expression:

The UHF bands IV/V are approximately one octave wide. This means that the required field strength at the upper end of the UHF bands is approximately 5 dB higher than at the low end to provide the same signal strength at the output of the antenna, for a constant-gain antenna.

dB

The following figures show the frequency dependence of a conventional rooftop receiver antenna for digital terrestrial television. Gain response of the antenna is compensated in order to avoid large imbalances between the received frequencies. However, radiation patterns measured for 5 frequencies show large differences in performance.

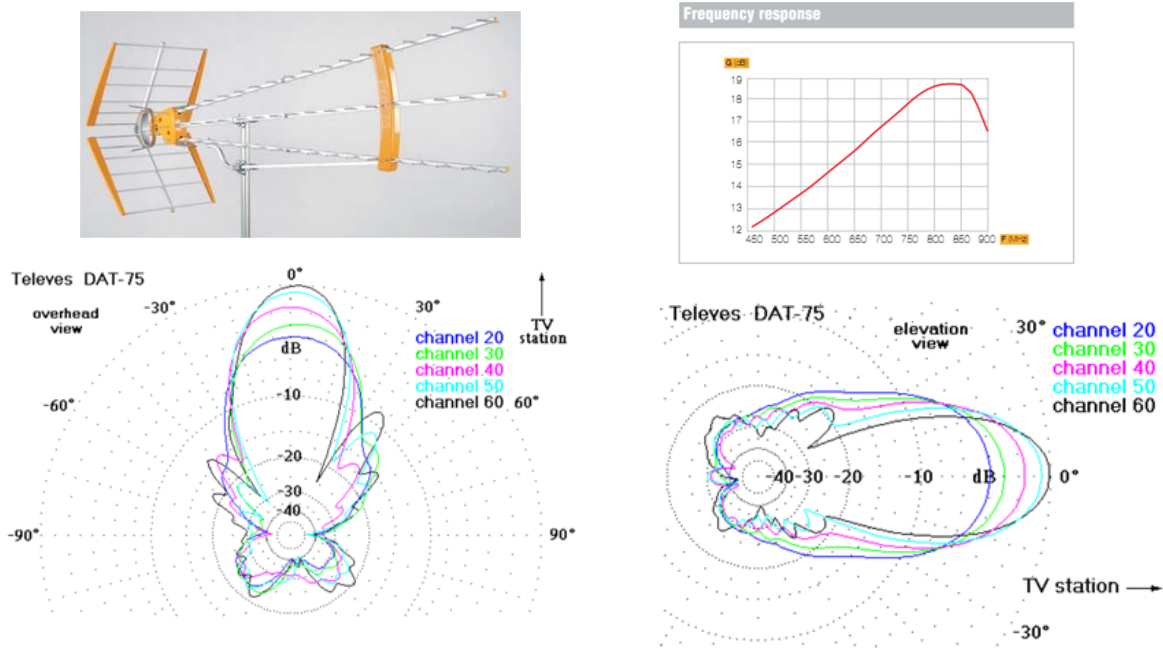


Figure 15. DTT antenna for fixed reception. Gain response and diagrams as a function of frequency.

As said before, antenna design for mobile and portable reception differs substantially from static antennas. These kinds of antennas are intended to be integrated in handheld receivers. Moreover, propagation conditions limit the presence of a strong signal contribution from the transmitter station. To guarantee reception of the signal, omnidirectional antennas have to be designed. Design dependences in frequency of mobile integrated antennas may also cause disturbances in the received signal. The figure below shows the variation of the antenna pattern for 4 frequencies in a UHF omnidirectional antenna design for handheld reception.

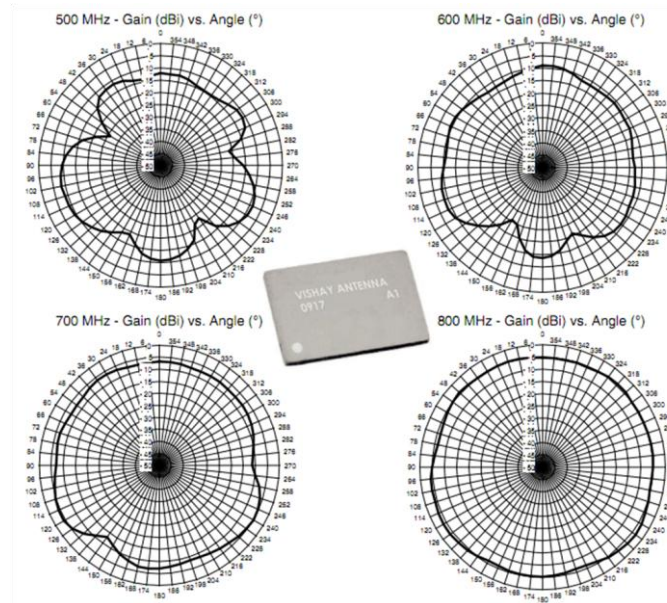


Figure 16. Gain variations with frequency for UHF mobile antenna

The main reason for the unequal coverage of the multiplexes in a DTT transmission is the signal level imbalances within the RF channels at the receiver input. However, these variations in the received C/N are not only constrained by antennas and propagation conditions as receiver noise can also have a harmful effect. In general, noise figure of the receiver may not be constant with frequency and it may change from RF channel to channel.

Measurements on receivers have shown that the upper UHF band usually have increased noise figure. Figure 17 presents the measured noise figure for four consumer receivers.

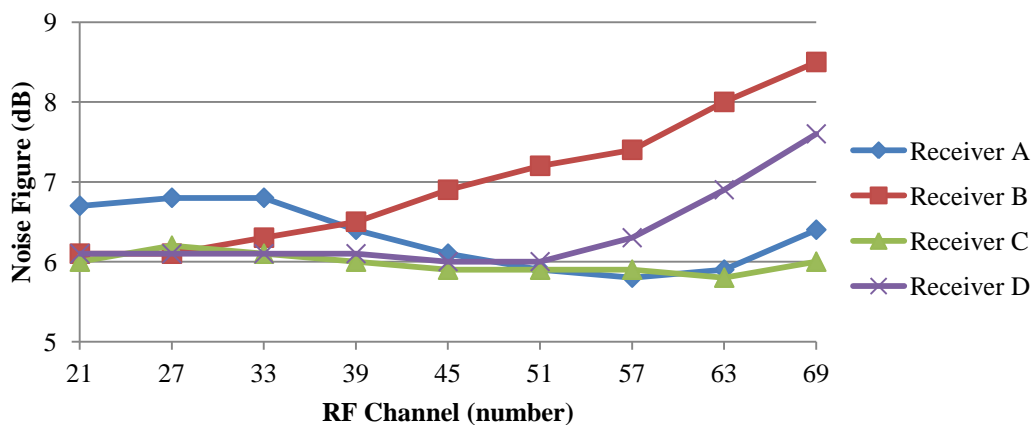


Figure 17. Noise figures of 4 receivers in the UHF band.

Simplified TFS model.

Correct reception of the complete DTT service offering is limited by the multiplex with the lowest signal strength at a particular location. With TFS, reception is more likely to be determined by the average signal strength since a particular service is spread over all involved RF frequencies in transmission. When there are large variations in signal strength between different RF signals the channels with high signal strength tend to compensate channels with low strength.

As a first approach, it may be feasible to consider that TFS gain may be calculated as the difference between the average signal strength and the worst signal strength (the RF channel with the poorest level).

Considerations on the coverage of the multiplexes.

TFS provides a coverage advantage for the RF channels with poor SNR level at a particular location. Thanks to frequency diversity broadcast services do not suffer from the same level of degradation during transmission as some parts of the service are transmitted in different RF channels and, as a consequence of the dependence of degradation sources with frequency, are not equally affected by disturbance. However, the effect of frequency diversity also concerns those RF channels with an acceptable SNR level. RF channels with poor SNR level will affect adversely the one with good level distorting their performance.



Deliverable 13.1 – TFS analysis, measurements and simulations

In a TFS transmission, there may exist locations where no program can be well decoded at all with TFS whereas the programs of the best multiplex can be entirely decoded without TFS. On the one hand, this implies a coverage reduction for the multiplexes with better SNR level. On the other hand, the coverage of the complete service offering is higher with TFS than with independent RF channels.

The reception of a digital service is characterized by the sudden loss of signal when it is highly degraded. Unlike analog signals, which gradually fade when signal-to-noise ratio decreases increases, a digital signal provides data which is either perfect or non-existent at the receiver side. In a transmission with multiple services over a set of multiplexes in the RF band, some of them may be highly attenuated making its reception impossible. With TFS such signal strength variations will however tend to be evened out so that all services can still be received, despite some of the RF channels may be below the acceptable signal strength level.

From the point of view of operators, it is difficult to market DTT services with significant different coverage of multiplexes in a given area. TFS bring the possibility of planning a network with homogeneous coverage and ensuring the availability of the complete service offering in the target area of service. From the point of view of consumers, they expect to receive the whole package of services. The reception of a random multiplex has little or no value for consumers as they expect to receive all services rather than a restricted set of them and certainly not only a single multiplex (which is not necessarily the one they would desire most). Therefore, TFS may suppose an advantage for the reception of the complete package of services as coverage impact of TFS is, in practice, only positive.

5.2 TFS Interference Gain

From the interference point of view, TFS can also provide a gain as the interferences from other transmitters are usually frequency dependent [2]. Such interference reduction can be exploited to improve the coverage in interference-limited areas, or to allow tighter frequency reuse patterns such that more DVB-NGH networks can fit within a given spectrum. In the T2 standardization process, interference gain was shown to exist in networks based on the frequency allocation plan GE'06, but it was not quantified.

TFS may also be beneficial to reduce potential interferences caused by the deployment of long term evolution (LTE) cellular services. LTE will use the upper part of the UHF band (channels 61-69) as the result of the digital dividend after the analogue switch-off. These transmissions may have an adverse effect on broadcast reception on RF channels close to LTE. However, using TFS, only a part of the signal (corresponding to the RF channels close to LTE) would be affected, and reception could still be successful, with only minor degradation in terms of required Signal-to-Noise Ratio (SNR) thanks to the reception of the other parts.

TFS gain can also be generated from interference. Although this interference gain is not directly related to the TFS coverage gain, it is obtained following similar mechanisms.

Signal from other stations sometimes limits the coverage in some parts of the DTT networks as a result of interference. The most important source of interference comes from stations broadcasting in the same RF channel (co-channel interference). Frequency plans for terrestrial broadcasting (such as Geneva plan, GE06)

Deliverable 13.1 – TFS analysis, measurements and simulations

are developed in order to limit the interference in the service area when there exist a certain number of networks in the same RF band. Interference increases with the number of networks co-existing in the RF band and as new networks are implemented some areas which were previously covered will find their coverage reduced as a result of increased interference level. In these cases, when the level of the interfering signal is higher than the receiver noise level for a certain RF channel, the reception of this frequency is interference limited rather than noise limited.

The interfering signals coming from a digital TV transmitter look like Gaussian noise and affect the received signal in the same way as the receiver noise. The wanted signals coming from a specific station, with nominally equal ERP, show large differences in level (C) for the different frequencies used, as a result of systematic and random, frequency-dependent, variations. The interfering signal level (I), coming from more distant stations, will, as a result of the same mechanisms, also suffer from these variations. The same type of advantage with TFS for the wanted signal C can also be applicable to the interfering signal I. Moreover, when interferences from other transmitters are statistically independent from the wanted signal, the resulting TFS gain is expected to be significantly larger than that considering field strength of the wanted signal only.

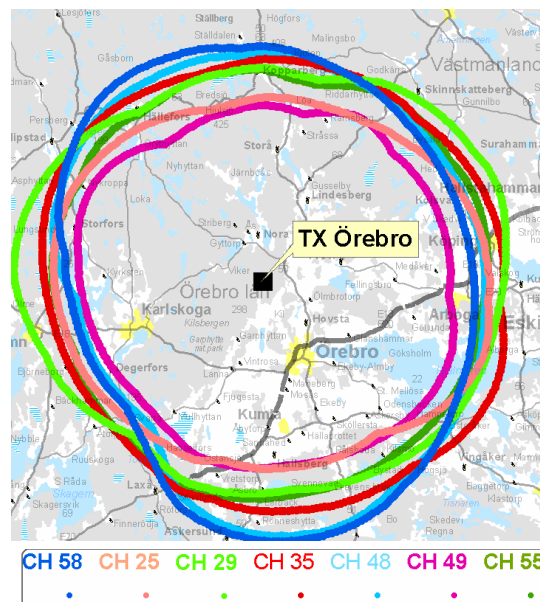


Figure 18. Coverage limited by interference in Sweden

Interferences from other transmissions do not affect the same frequencies in a network as not all transmitters in the same area broadcast using the same RF channels. That means interference in a TFS transmission would not affect all multiplexes. Moreover, the level of interference not only depends on location but also on time. As a result of atmospheric conditions, interference can propagate long distances. This effect, known as tropospheric propagation, is increased during a small fraction of the year and can also affect a subset of the TFS frequencies. TFS gain can be obtained taking advantage of frequency dependent disturbances.

This TFS interference gain can be exploited either as better coverage or, potentially to allow a more efficient frequency reuse, enabling more services to be squeezed into the available frequency band.

6 SPECTRUM EFFICIENCY INCREASE BY IMPROVED INTERFERENCE PERFORMANCE AND OPTIMIZED NETWORK DESIGN

6.1 Introduction

A study has been conducted at Teracom, as part of a Bachelor of Science thesis [12], to evaluate the potential spectral-efficiency gains of using TFS in interference-limited multi-frequency networks (MFNs) built with a regular pattern of identical and equidistant omni-directional transmitters in a hexagonal lattice. Each hexagonal area has a single transmitter positioned in the center of the hexagon.

To cover an arbitrarily large area with such an MFN the network needs to have a frequency reuse with a certain frequency reuse factor N . This means that N frequencies (e.g. UHF channels) are used to build the network of one multiplex using a single RF channel per multiplex and site (non-TFS). With M multiplexes there will be M frequencies per site and a total of $M \cdot N$ frequencies are required to build the complete M -multiplex network. Using TFS each site uses instead M frequencies, with each of these being reused in the same way as in the non-TFS case. Again a total of $M \cdot N$ frequencies are used to provide a TFS “super multiplex” using M frequencies per site.

In an MFN the wanted transmitter will provide a certain field strength in the reception point. Correspondingly, all other transmitters in the network using the same frequency will provide an interference contribution to the same reception point, see Fig. 19.

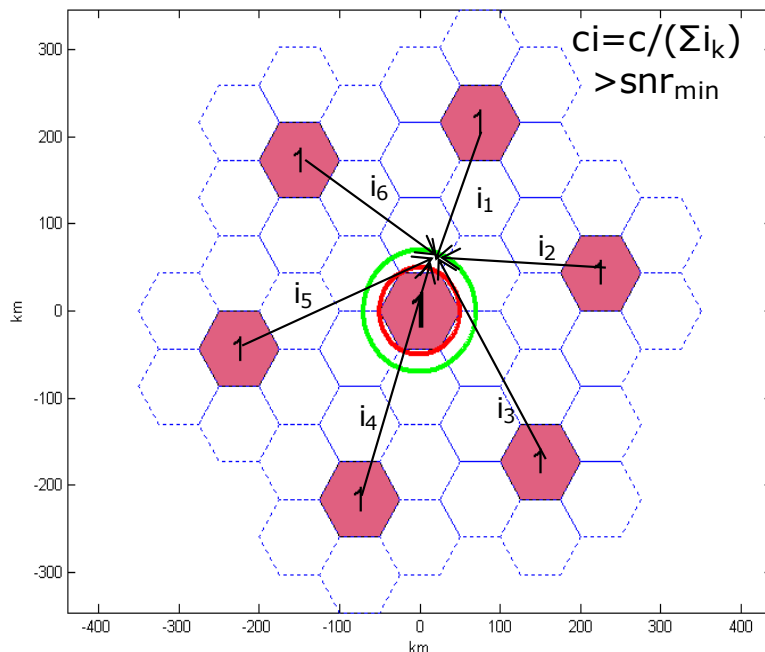


Figure 19. The linear c/i in the reception point is given by the ratio of the wanted power c to the sum of all interferers i_k . The C/I in dB is then given by _____ and the normalized (b/s/Hz) Shannon channel capacity within the used channel by _____ .

All these interferers will add and the ratio of the wanted power to the total interfering power yields a carrier-to-interference ratio (c/i) in the reception point, which determines, via Shannon, the maximum capacity (channel capacity) that can theoretically be transmitted to this reception point. The higher the value of N , and therefore the larger the distance to interfering transmitters, the higher the c/i and the resulting channel capacity. Conversely, the lower the value of N , the lower the c/i and the lower the channel capacity.

What should be kept in mind is that within a fixed given total spectrum the number of useful frequencies (“multiplexes”) also depends on N so that a lower value of N allows for a larger number of useful frequencies per site. This means that what should be maximized is the product of the number of useful frequencies per site and the capacity per site. A certain value of N will maximize this product and the figure of merit is the spectral efficiency S thereby obtained, defined as the total capacity divided by the total used spectrum (bit/s/Hz). This is the maximum spectral efficiency that can be achieved with the current network, assuming the C/N is high enough so that effect of noise on coverage is negligible. In such a network coverage is not affected by e.g. doubling the power of all transmitters, since C/I will stay the same.

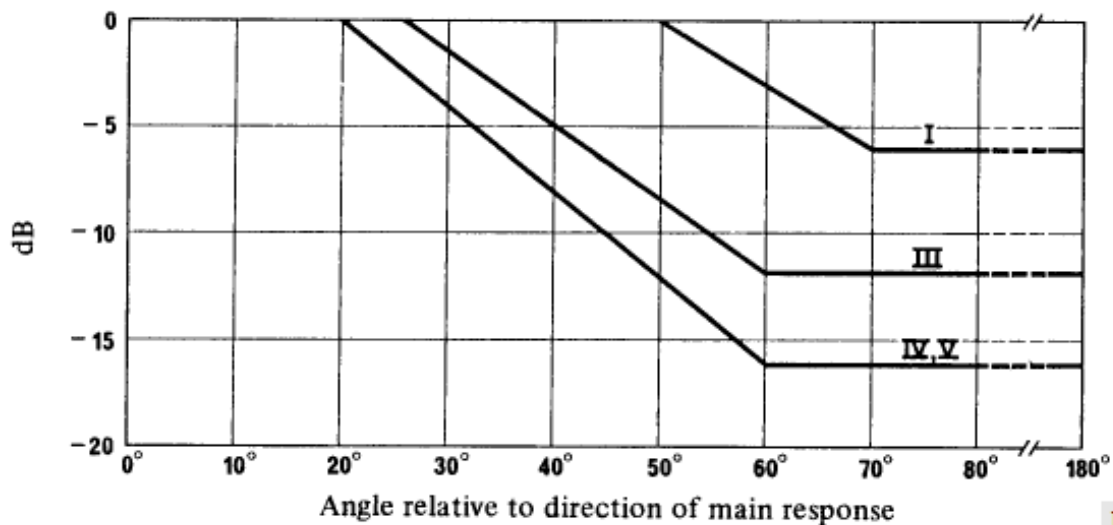
From the point of view of interference-limited coverage the results of the study of course depends on the requirements for coverage. The lower the coverage requirements the higher the (nominal) spectral efficiency will become, and vice versa. There are many possibilities to set coverage requirements but the assumed requirements adopted in this study was to require the reception of all transmitted services (over M frequencies per site) with 95% probability³ in the “worst” point of the hexagon, i.e. the point with the lowest Shannon channel capacity, given the C/I values in this point. If this condition is fulfilled then a broadcast mode could in principle be chosen (assuming an ideal system) having this capacity, which would be receivable everywhere in the hexagon, i.e. having >95% probability of receiving all services in any point of the hexagon.

Propagation model

The propagation model used for the study was ITU-R Rec. 1546 [13] which defines the received electrical field strength at a certain distance from a 1 kW ERP transmitter given e.g. the effective antenna height, frequency, height of receiver antenna, terrain type and percentage of time.

The “effective antenna height” is the height of the antenna above terrain height averaged between distances of 3 to 15 km in the direction of the receiving antenna. Since it is generally advantageous to have a high effective antenna height, broadcast sites are often positioned such that the effective antenna height is significantly higher than the transmitter mast itself. In Sweden, typical “main transmitter” mast heights are 300 m and the average effective antenna height is 400 m. In the study, two values for effective antenna height were used: 400 m and 250 m. Reception was always assumed at 10 m above ground level with a directional antenna having the characteristics of ITU-R recommendation BT.419-3 [14], i.e. with an opening angle of +/-20 degrees relative to the direction of the wanted transmitter and with linearly increased discrimination up to 16 dB at +/- 60 degrees, see Fig. 20.

³ The probability refers to the reception of all services *globally* and not per individual multiplex. Having a 95% reception probability of each individual multiplex yields a probability that is lower than 95% to receive all services.



D01-sc

Figure 20. Antenna discrimination according to ITU-R Recommendation BT.419-3, for signals having the same polarization as the antenna (picture taken from the ITU recommendation).

It should be noted that, since only C/I is considered in the study, the absolute gain (frequency dependent or not) of the transmitting and receiving antennas becomes irrelevant, since wanted and interfering signals are affected equally by this. The received C/I on a particular frequency is therefore the same as the difference in dB between the received wanted field strength and the (total) received interfering field strength. What is very important however, is the antenna *diagram* of the receiving antenna, since this varies with direction; and wanted and interfering signals typically arrive from different directions, so the receiving antenna will discriminate them differently.

The desired transmitter antenna diagram is typically omni-directional. Realistic transmitting antenna diagrams are however typically far from this, especially if they are to cover a wide frequency band. Real antennas tend to have significant selectivity depending on direction and this selectivity is also frequency dependent. In this study the transmitter antenna diagram was modeled as omni-directional, but the effects of real antennas were instead incorporated in a general frequency-dependent log-normal fading term also including other effects, see below.

The frequency band was always UHF band IV/V (470-790 MHz) with the used frequencies from each transmitter being evenly distributed over this band.

In addition to the deterministic propagation model given in ITU-R Rec. 1546, reception must also take into account fading, which needs to be statistically modeled. The total received field strength of the wanted signal as well as of all interferers is given by the deterministic field strength with an additional dB term for frequency-independent but directional-dependent *shadow fading* and another additional dB term for frequency-dependent fading, which is unique for every transmitter. Shadow fading and frequency-dependent fading are modeled statistically in the following way:

Shadow fading

Shadow fading is modeled as log-normally distributed (i.e. having a Gaussian distribution in dB) with a standard deviation of 5.5 dB in all cases. This also follows from ITU-R Rec. 1546. The shadow fading is assumed to be independent from different directions, but from a given direction all frequencies originating from a particular site are assumed to have the same shadow fading (i.e. frequency independent). If one signal is e.g. 10 dB stronger than the deterministic value due to shadow fading then *all frequencies* from that transmitter are received with a 10 dB increase in field strength. However, all signals from other interfering transmitters will have an independent value of the fading following the lognormal distribution. Also other values than 5.5 dB for the shadow fading were tested in the study.

Frequency-dependent fading

As mentioned above, real transmitting antennas will introduce a sort of frequency dependent fading. Also the effects of the wave propagation (multipath) and the positioning of the antenna are frequency dependent. All these effects are modeled as an additional frequency dependent fading of 2 dB. According to [10] the standard deviation of the imbalance between two received RF channels with a certain frequency separation is in the range 2.5 dB – 5 dB. Assuming a standard deviation of each RF frequency of 2 dB is consistent with the results presented in [10]. Also other values than 2.0 dB for the frequency-dependent fading were tested.

6.2 Use cases

As a reference for the performance gain, the spectral efficiency of non-TSF was used for a frequency reuse of $N=7$ and with horizontal polarization everywhere, since these are the “classical” broadcast parameters and the ones that most resembles the actual situation. From each site six frequencies were used ($M=6$). It should again be noted the coverage requirement to receive “all services” (=all multiplexes). The relevance of this requirement is that this corresponds to the highly commercially desirable requirement that a terrestrial user, which may also be a paying subscriber, normally expects to receive the full terrestrial content (that he/she is entitled to view). A user that does not receive all multiplexes, and in particular all multiplexes that he/she has paid for, may not remain a terrestrial user, but may move to competing distribution media.

To improve the spectral efficiency upon this reference case three new technical ideas, developed at Teracom, were simulated in different combinations:

- TFS
- TFS with multiple frequency reuse patterns (MFRP)
- TFS with mixed polarization network (MPN)
- TFS with MFRP and MPN

TFS

For the basic TFS case, horizontal polarization and a single (common) frequency reuse pattern were used for all M TFS frequencies from each site. For $N=4$ the frequency reuse pattern in Fig.21 was used.

From the center hexagon (where the wanted transmitter is situated) all surrounding interfering transmitters appear at the same distance from the wanted transmitter. Since both the wanted signals and all interfering signals from a particular interfering site will be affected by independent frequency-dependent fading the resulting C/I will vary among the TFS frequencies. In the reference case the frequency with the worst C/I will determine the spectrum efficiency whereas in this case the spectrum efficiency is determined by the

average of the spectrum efficiencies for the individual TFS frequencies. One totally destroyed frequency will still allow high spectrum efficiency provided the other TFS frequencies have good enough C/I. A TFS gain with respect to C/I is therefore to be expected, which can be exploited as an increased spectral efficiency.

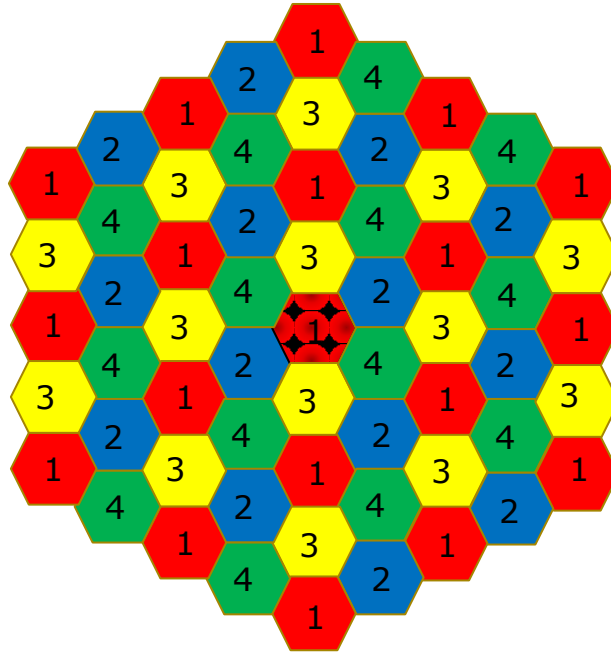


Figure 21. Optimum frequency reuse pattern with N=4 (Single frequency reuse pattern, non-TFS and TFS)

TFS with multiple frequency reuse patterns (MFRP)

In this case, the TFS frequencies have different frequency reuse patterns in the network. For N=4 the three patterns shown in Fig. 22 are used.

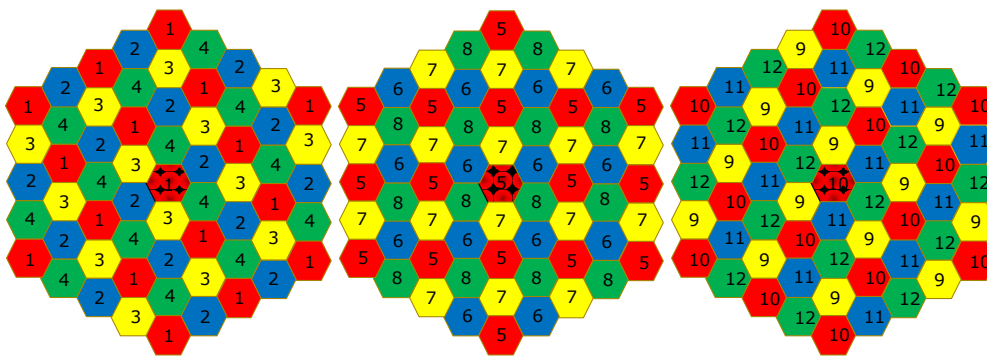


Figure 22. The three frequency reuse patterns for N=4 (multiple frequency reuse pattern, TFS). The center hexagon uses TFS with the “red” frequencies 1, 5 and 10, which each has a different reuse pattern. The same principle applies to any other hexagon.

For M=3 this means that each TFS frequency gets a unique frequency reuse pattern. For M=6 each pattern is used by two TFS frequencies (M=9, three frequencies, etc). It can be noted that pattern two and three in Fig. 22 are rotated versions (120 and 240 degrees) of the first pattern and that the three patterns are equally good



Deliverable 13.1 – TFS analysis, measurements and simulations

(or bad!) if used for non-TFS, but worse than fully symmetric pattern in Fig. 21. With $N=7$ (not shown here) any rotation of the basic fully symmetric pattern yields the same pattern. However, this basic pattern can be *mirrored* to an equally good pattern, also fully symmetric. When TFS is used with $N=7$ the TFS frequencies may therefore get alternatively the two patterns, so that with e.g. $M=6$ each pattern is used three times.

Thanks to the varying frequency reuse patterns interference contributions from a particular neighboring transmitter will only affect (for $N=4$) *one third* the TFS frequencies (the closest interfering transmitter in the “north-east” direction from the center in pattern 1 of Fig. 22 only exists at that position with that pattern but not in the other two patterns!). If the received interference from that transmitter happens to be very strong (mainly due to shadow fading) this can be compensated for if the C/I is good enough on the other two thirds of the TFS frequencies from that transmitter. Furthermore, using a directional receiving antenna will increase the likelihood that only one (if any) received direction will have strong fading. It should however be noted that each of the patterns in Fig. 22 are unsymmetrical, and therefore individually sub-optimum. With $N=4$ the closest interfering transmitter will e.g. be closer than using the fully symmetric pattern in Fig. 21 but the described positive effects will, as we will see, more than compensate for this, with a net positive gain in spectral efficiency. For $N=7$ both patterns are optimum so the problem does not occur and there is an obvious spectral efficiency increase by using two alternating patterns.

Also for this case horizontal polarization was used for all TFS frequencies. The fully symmetric pattern shown in Fig. 21 is not applicable for use (alone) with the multiple-frequency-reuse patterns method since rotating or mirroring this pattern yields the same pattern. One can therefore not construct multiple *different* frequency reuse patterns with this basic pattern. However, for $N=4$ and with M *not* being a multiple of three (e.g. $M=2, 4$ and 5) one cannot use all three patterns in Fig. 22 with equal proportions. It is likely (although not proven) that in this case the optimum configuration is to use only the pattern in Fig. 21 (for $M=2$) or use a multiple of the three patterns of Fig. 22 together with one or two times the pattern in Fig. 21. With e.g. $M=5$ one could use the three patterns of Fig. 22 together with two times the use of the pattern in Fig. 21. In this way one can apply this method for any value of $M>2$ and with optimum performance for M being multiples of three TFS frequencies (3, 6, 9, etc).

TFS with mixed polarization network (MPN)

The receiving antenna, according to ITU-R Rec. BT.419, has a discrimination of 16 dB (for any direction) with respect to signals of the opposite polarization arriving within the opening angle ± 20 degrees.

For signals of opposite polarization coming from directions where there is a significant additional discrimination compared to signals having the same polarization as the wanted signal, a corresponding reduction of the interference level is achieved. It would therefore in general be desirable to have as many as possible of the strongest interferers using the opposite polarization. The studies have found that using pairwise the same polarization in hexagon columns (see Fig. 23) provides a near optimum performance together with the methods described here.

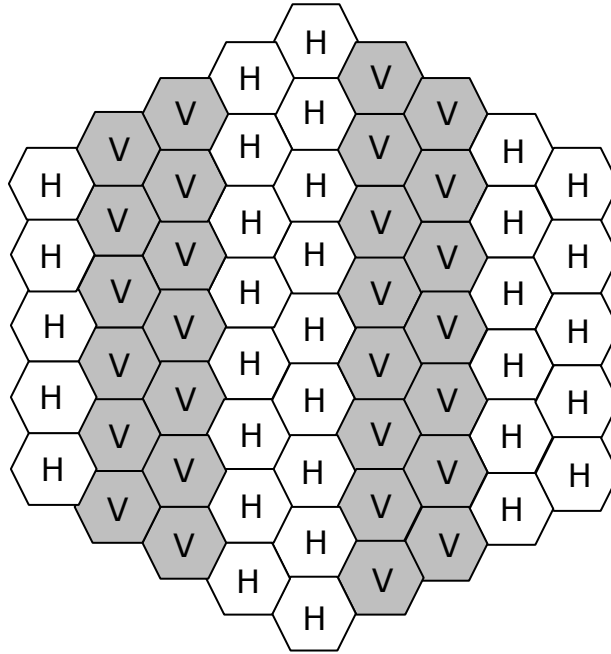


Figure 23. Pattern of polarizations to be applied to hexagons for mixed polarization networks (non-TFS or TFS)

TFS with multiple frequency reuse patterns and mixed polarization network

In this case both of the above-described additional methods (MFRP and MPN) are combined with TFS.

The combination is straight-forward: overlaid, on top of the frequency reuse patterns in Fig. 22, the polarizations in Fig. 23 are applied. The resulting frequency reuse patterns with polarizations are shown in Fig. 24. It should be noted that only 2 (two patterns) or 3 (one pattern) of the 8 closest interfering transmitters use the same polarization as the wanted transmitter, which significantly reduces the received interference.

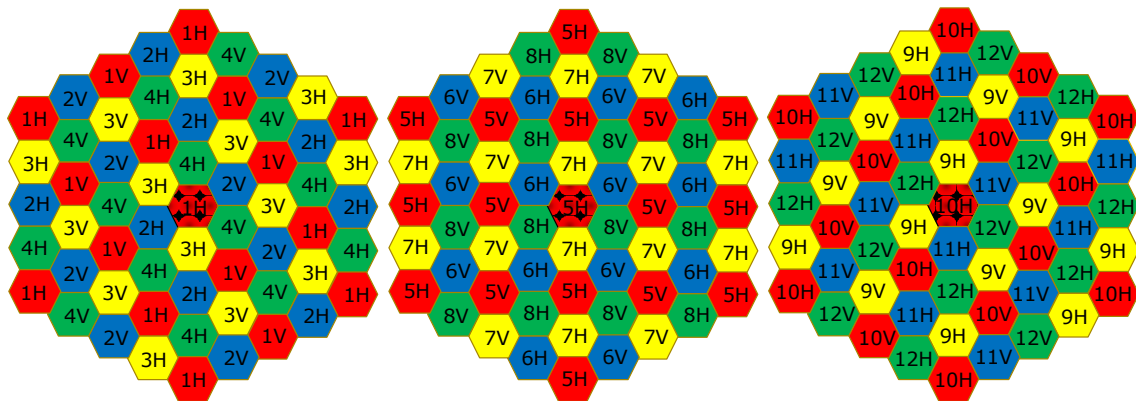


Figure 24. The three frequency reuse patterns of Fig. 22, together with applied polarizations according to Fig. 23.

It should be emphasized that for all TFS-based methods described in this study the transmitted signal from each transmitter is in line with “classical TFS”, i.e. a signal according to Annex E of the DVB-T2 spec [3] or according to the NGH spec (LC Type D) [15] could be used without any further modifications. The additions are purely network related, with an optimization of number of frequencies, frequency reuse patterns and the use of mixed polarization in an optimum way. Nothing special is therefore required from the standardization

or receiver implementation point of view to support TFS with multiple frequency reuse patterns and/or TFS with a mixed polarization network provided the basic TFS functionality is supported.

6.3 Computer simulations

To evaluate the spectral efficiency for different network configurations and other conditions, computer simulations were carried out in the form of Monte Carlo simulations. In a certain reception point, the path losses from all relevant⁴ transmitters were calculated according to [13] as well as a large number K (typically K=100 000) of realizations from the log-normal fading distributions. The same realization of the shadow fading was used for all frequencies from a transmitter but different realizations for the frequency-dependent fading. In this way it was possible to get K realizations of the wanted transmitter as well as of all interfering transmitters. For each realization, the interference contributions were added and the C/I could be calculated as well as the corresponding spectral efficiency of the individual realization. In this way one could obtain K realizations of spectral efficiency for each used RF frequency. In the TFS case, the global spectral efficiency was obtained as the average of all the M TFS frequencies. The spectral efficiency that was considered available in the reception point was the one that was available with 95% probability (or corresponding percentage when another value was used). The representative value for the hexagon was the spectral efficiency in the worst point in the hexagon. A special procedure was used to find the worst point quickly so that not all the processing mentioned above would have to be performed for all points in the hexagon.

Results

In Table 2 and 3 the results of the study are summarized with Table 2 showing the absolute spectral efficiency and with Table 3 showing the percentage gain in spectral efficiency compared to the case with N=7 and non-TFS with six frequencies and horizontal polarization, which is similar to real DTT implementations.

Table 2. Spectral efficiency (b/s/Hz) for N=4 and 7 for the different investigated methods. Transmitter distance = 80 km and effective antenna height = 400 m.

Method	N=4	N=7
Single frequency	1,34	1,17
Non-TFS: 6 frequencies	1,11	1,03
Non-TFS: 6 frequencies +MPN	1,37	1,20
TFS: 6 frequencies	1,38	1,19
TFS + MPN	1,48	1,30
TFS + MFRP	1,42	1,22
TFS + MPN + MFRP	1,54	1,32

⁴ i.e. significantly affecting the results.

Table 3. Spectral efficiency gain (% increased b/s/Hz) relative to the reference case with N=7 and non-TFS (6 frequencies) for N=4 and 7 for the different investigated methods. Transmitter distance = 80 km and effective antenna height = 400 m.

Method	N=4	N=7
Single frequency	30%	14%
Non-TFS: 6 frequencies	8%	-
Non-TFS: 6 frequencies +MPN	33%	17%
TFS: 6 frequencies	34%	16%
TFS + MPN	44%	26%
TFS + MFRP	38%	18%
TFS + MPN + MFRP	50%	28%

6.4 Conclusions

In addition to the well-known TFS StatMux and coverage gains the presented study shows that in a theoretical hexagonal network TFS may provide very large improvements in fundamental spectral efficiency for interference-limited networks. Furthermore, by optimizing the network planning, i.e. choosing the right frequency reuse factor, using multiple frequency reuse patterns and mixed polarization networks it is possible to increase the spectral efficiency with 50%, compared to a reference case with seven frequencies, for interference limited MFNs with transmitter separation of 80 km and effective transmitter height of 400 m.

7 TFS PERFORMANCE EVALUATION FROM MEASUREMENTS

7.1 Measurement Settings

The Swedish DTT network operator Teracom performed indoor and outdoor measurements in different areas of the DVB-T network in Sweden. Both sets of measurements consist of samples of the signal strength of 4 and 6 multiplexes which are recorded cyclically. The power level measured in each channel is represented as the relative level of each one to the average level of all the channels, see Fig. 25. Outdoor measurements only take into account variation in the signal level caused by path loss. The variability of the signal cannot be evaluated over time, and no fast-fading effect can be analyzed. Indoor measurements take into account variations in time. The signal differences in each measured RF channel comes from path loss and fast-fading.

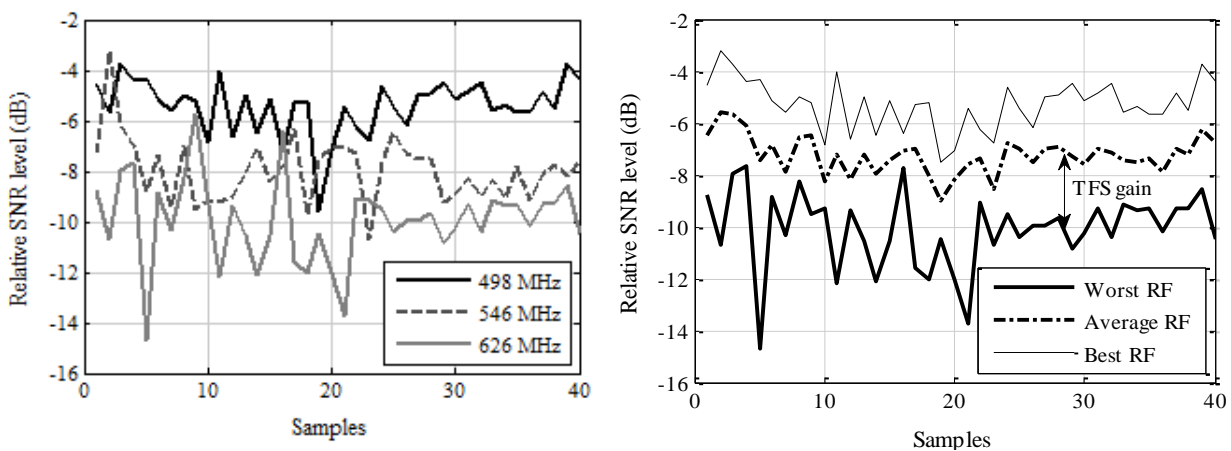


Figure 25. Samples of the outdoor measurements of three RF channels (left) and maximum, average, and minimum signal level among the three RF channels (right).

7.2 TFS Coverage Gain Definition

Simplified Model for the TFS Coverage gain

When a collection of DTT services is transmitted over several different multiplexes, correct reception of all these multiplexes is required in order to receive all services. Without using TFS, the coverage and, therefore, reception of the services broadcasted over a set of multiplexes is limited, at a given location, by the multiplex with the lowest signal strength at a particular location. In mobile scenarios, as it has been explained, good reception of all multiplexes is not guaranteed over the time as propagation effects (e.g. shadowing, fast-fading, etc) cause instantaneous signal fluctuations. That means that at a particular location, the worst multiplex may not always be the same.

When using TFS, reception at a particular location is more likely to be determined by the average signal strength of the RF channels through which services are distributed as the bits of the received signal have been affected by the particular SNR of the RF channel. Therefore, with appropriate coding and interleaving even a fully lost RF channel may still allow correct reception of all services. What matters for reception is therefore basically the “global” quality of all OFDM cells within the interleaving depth, and not so much a

particular RF channel. When there are large variations in signal strength between different RF signals the “good” RF channels therefore tend to compensate the bad ones.

Assuming that the receiver obtains the signal by means of frequency hopping and that the signal is composed by time bursts which have been transmitted over a different RF channels, TFS gain may be defined as the difference between the average signal-to-noise ratio (SNR) of the N channels involved in transmission and the worst RF channel (the one with the poorest SNR) for each particular location:

where SNR_i is given in linear scale and SM stands for Simplified Model. is calculated as follows:

—

Analysis of the TFS coverage gain from an Information Theory point of view

The information theory helps to quantify the theoretical limits of the increased diversity when using TFS. The maximum bandwidth normalized channel capacity C is given by the Shannon-Hartley theorem as:

where the SNR (signal-to-noise ratio) is given in linear scale.

With the different QAM mappings that are used in DVB-NGH or DVB-T2, capacity is bounded by the maximum spectral efficiency of the given QAM mapping (e.g. 2 bps/Hz for QPSK or 4 bps/Hz for 16-QAM). However, these curves come quite close to the maximum capacity for the non-saturating areas.

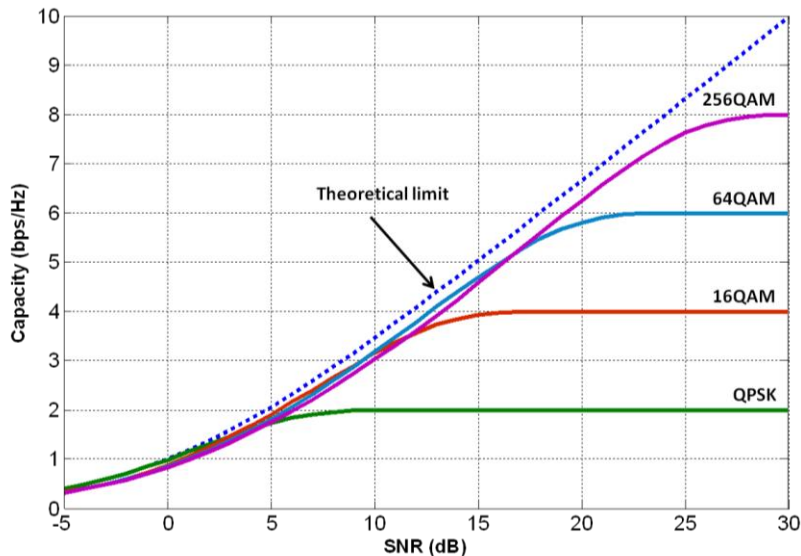


Figure 26. Capacity curves as function of the SNR for different modulation schemes.



With these figures, the required SNR for error-free reception in an AWGN channel can be calculated. According to Shannon, error-free transmission using an ideal communication system is possible if $C > R$ where R is the bandwidth normalized rate of the transmission. In an example using 64 QAM with a FEC coderate of $2/3$, $R = 6 \text{ bps/Hz} \cdot 2/3 = 4 \text{ bps/Hz}$. According to Figure 26, this value corresponds to $\text{SNR}=12.7 \text{ dB}$, which would be required for error-free reception with an ideal transmission system.

These equations can be used to estimate the achievable gain of TFS in N AWGN channels having different SNR:

—

in which C is the average Shannon capacity and C_i is the Shannon capacity of the RF channel i , which depends on the SNR of this RF channel.

This can be reformulated into:

— — —

An equivalent SNR can be defined through the development of the product in the equation. Equivalent SNR would characterize the equivalent RF channel of a TFS transmission that takes into account the SNR of the N RF channels involved in transmission.

— —

Note that for high SNR the TFS capacity is approximately the capacity of an equivalent channel having the average SNR in dB scale as the equation may be simplified when $\gg 1$:

— —

A new expression may be used to calculate TFS gain according to the equivalent SNR obtained by means of Information Theory instead of the TFS gain calculated using the average SNR of the RF channels. Table 4 summarises the resultant equations for the calculation of the theoretical TFS coverage gain considering the two models already explained.

Table 4. Formulas for the calculation of the TFS gain

	Calculation of the SNR	Calculation of the TFS gain
Simplified SNR Model	—	
Equivalent SNR Model		

7.3 Evaluation of the TFS gain from field measurements

Outdoor Measurements

First, we investigate the TFS gain when only two RF channels are used in the TFS multiplex, and evaluate the influence of the frequency spacing among them. Fig. 27(a) shows the average TFS gain as a function of the frequency spacing. Fig. 27(b) shows the Probability Density Function (PDF) of the TFS gain for six different frequency spacing values. In Fig. 27(a) it can be observed that, in general, the TFS gain increases linearly with the channel spacing between two RF channels for all the transmitter areas. A 3 dB gain is achieved for 112 MHz (14 channels in-between). In Fig. 27(b) we can see that there are some locations where there is no TFS gain. But the percentage of locations is below 6% already for a separation of 6 channels.

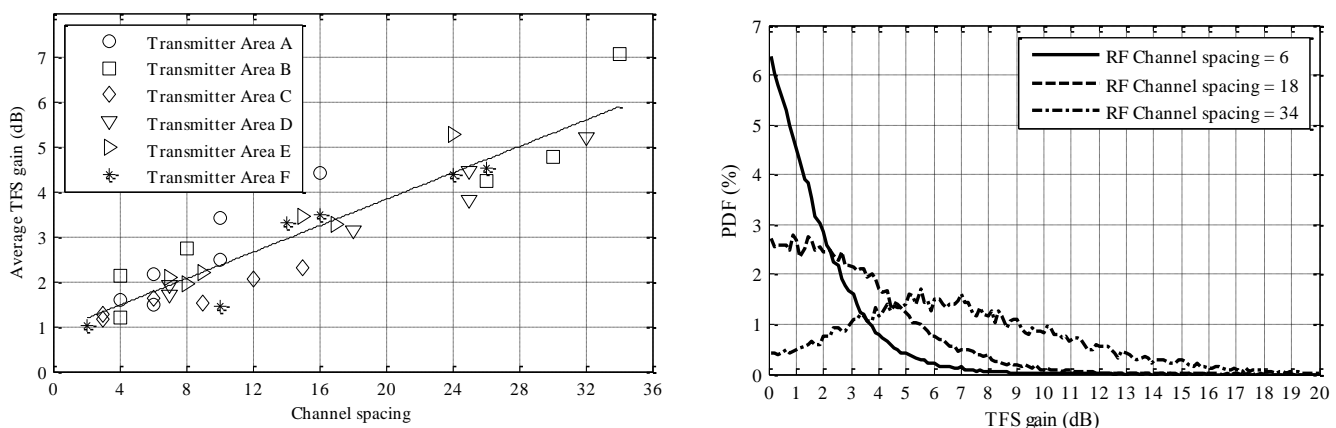


Figure 27: Average TFS gain for two RF channels as a function of the frequency spacing (left) and probability density function of the TFS gain for different frequency spacing.

Fig. 28 shows the probability density function of the TFS gain for 2, 3 and 4 RF channels in the TFS multiplex using all the possible combinations of frequencies available from the measurements. We can see that very important gains can be achieved. The PDF of the TFS gain for 3 and 4 RF channels resemble a

Rayleigh distribution, whereas for 2 RF channels it resembles an exponential distribution.. The average TFS gain is 2.5 dB, 4.3 dB, and 6.2 dB, for 2, 3, and 4 RF channels, respectively.

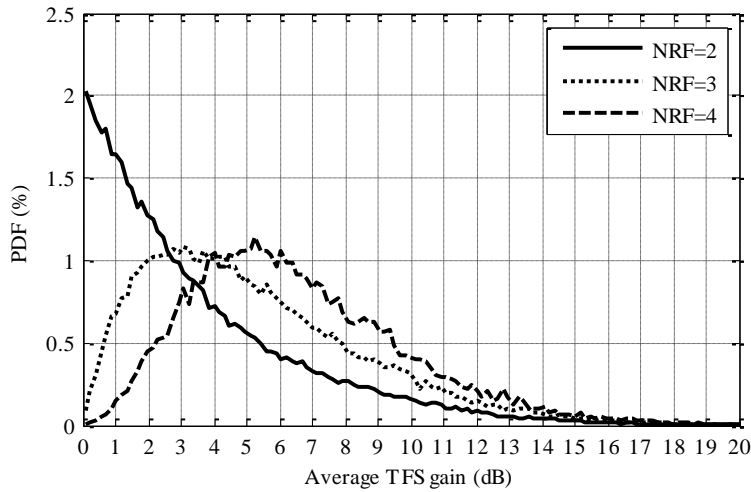


Figure 28. Probability density function of the TFS gain with different RF channel aggregations.

Indoor Measurements

Fig. 29 shows the average TFS gain of a TFS multiplex with two RF channels as a function of the distance to the window for three different frequency spacing values: 8 MHz, 112 MHz, and 264 MHz, (1, 14, and 33 channels respectively). Indoor reception presents the particularity that the signal level varies strongly with frequency due to penetration losses into buildings. Hence, larger gains can be expected for indoor reception than for outdoor reception. With a very narrow spacing among the two channels (8 MHz), the TFS gain is reduced when moving away from the window because the building penetration loss evenly reduces the signal level of the two channels. But with a wide spacing (33 MHz), the TFS gain increases with distance to the window. The reason is that the signal level of the worst channel decreases significantly faster.

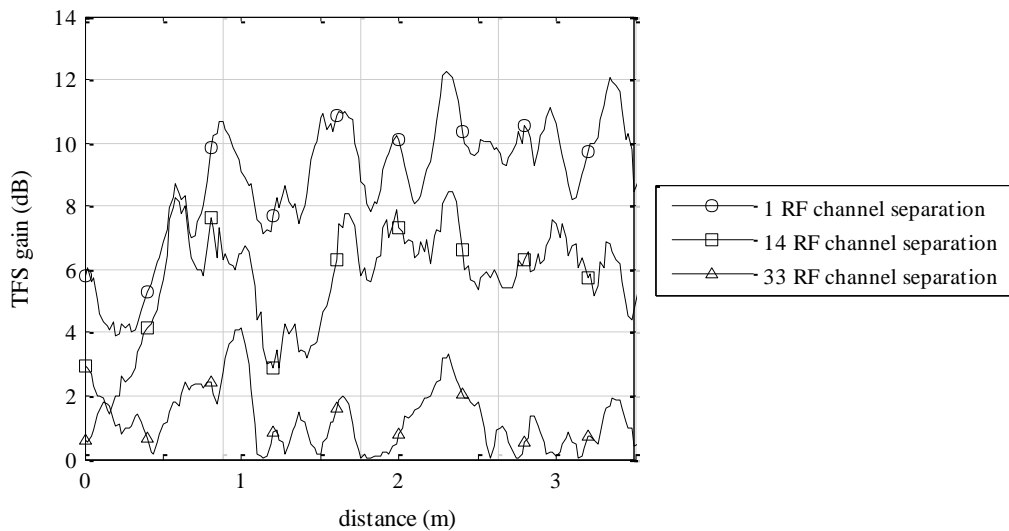


Figure 29. TFS gain for 2 RF spaced channels as a function of the distance inwards the building (1, 14 and 33 MHz channel separation).

Optimal Spectrum Allocation with TFS



Deliverable 13.1 – TFS analysis, measurements and simulations

The presented results reveal the importance of spreading the RF channels of a TFS transmission as evenly as possible over the UHF band. In general, the coverage level is higher at lower frequencies, but the coverage requirement for all services is normally the same. This means that when several independent TFS transmissions are used they should have the same coverage and therefore RF frequencies “equally” spread over the UHF band. If e.g. two TFS transmissions would be placed in the lower and upper half of the UHF spectrum, the differences between the RF channels of each TFS transmission would be lower than if these frequencies were distributed over the full UHF band, which is in itself an advantage. However, the global coverage would be quite different between the lower and the upper half TFS signals. In such a multiple TFS transmission scenario, it is recommended to spread the frequencies of each TFS signal as evenly as possible over the UHF band. This will maximize frequency diversity and will ensure the same coverage of these TFS transmissions. Also from a point of view of “equality between countries”, it is natural to allocate frequencies to all countries as evenly as possible over the UHF band.

8 TFS PERFORMANCE BASED ON PHYSICAL LAYER SIMULATIONS

8.1 Simulation Settings

The performance of TFS has been evaluated with physical layer simulations to investigate the effect of the code rate, rotated constellations, and the power imbalances among the different RF channels. The simulator has been calibrated within the NGH standardization process. Table 5 shows the main configuration parameters of the simulations.

Table 5. PHY simulations configuration for the TFS performance evaluation.

FEC Configuration						
Code Rate	1/3 7/15 2/3		FEC blocks per frame	49		
Bits per Cell (Modulation)	QPSK		Rotated Constellations (2D)	Enabled – Disabled		
FEC type	16200					
Time Interleaving Configuration						
Sub-slices per frame	1620		Time Interleaver	Activated		
Frame Interval	1		Component Interleaver	Activated		
Convol. Interleaving length	Num. of RF channels		Convol. Interleaving type	Uniform		
OFDM Generation Configuration						
FFT Size	8K carriers	(6817)	Guard Interval	$\frac{1}{4}$	Bandwidth	8 MHz
Channel Configuration						
Channel Model	Typical Urban 6	Doppler frequency	33.3 Hz	Antenna Configuration	SISO	
System Configuration						
Number of frames	500					
Frame length	250 ms					

Although in a real transmission the reception conditions in each RF channels might vary dynamically from frame to frame, in our simulations it is considered that some channels of the TFS multiplex suffer from static imbalances. The operation of TFS is emulated at the receiver by means of applying a different Carrier-to-Noise Ratio (CNR) level to each frame. Fig. 30 represents a transmission using TFS with 3 RF channels in which one frame is received with a lower CNR level. The number of interleaved frames is equal to the number of RF channels.

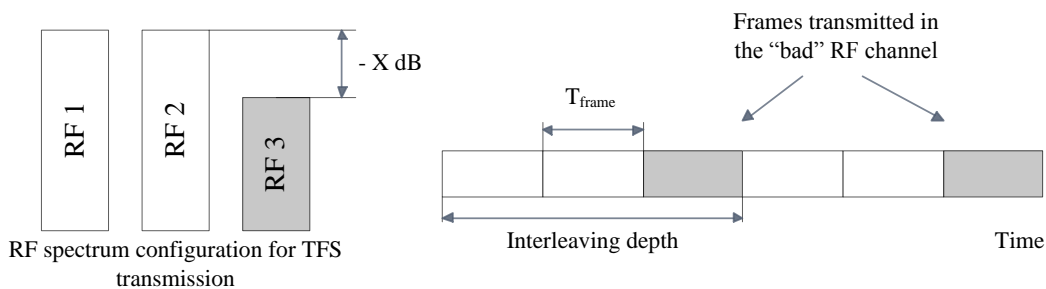


Figure 30. Emulation of the TFS operation for the PHY simulations.

8.2 Results

Influence of the Code Rate in the TFS Performance

In this section the performance of TFS is evaluated for different code rates. The code rate defines the redundancy applied to the information data to cope with disturbances in the received signal and, thus, it plays an important role in the TFS operation because it determines the capability to recover from “bad” RF channels.

Fig. 31 shows the Frame Error Rate (FER) as a function of the CNR for different transmission configurations and different code rates (1/3, 7/15 and 2/3). The TFS multiplex is assumed to have four RF channels, with two of them having an imbalance (attenuation) of -6 dB with respect to the other two. In the figure, the solid lines refer to the performance of the TFS transmission. The dotted lines represent the performance of the RF channel with the lowest CNR value (in this particular case, -6 dB).

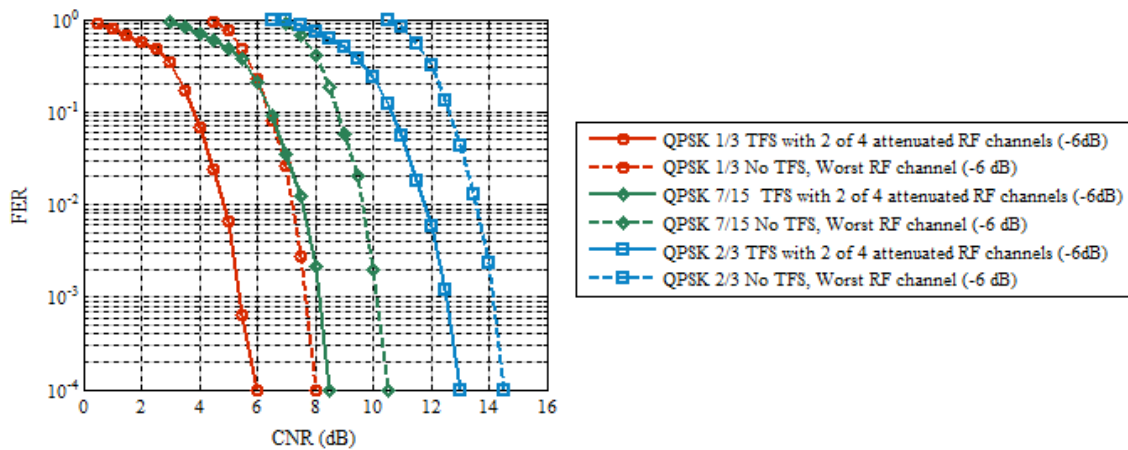


Figure 31. Simulated TFS performance with four RF channels for different code rates. Two channels are attenuated -6 dB with respect to the other two channels.

In the figure, we can see that the TFS gain increases when reducing the code rate (i.e., increasing the transmission robustness). The gain values at $FER = 10^{-4}$ are 2 dB, 2 dB, and 1.5 dB, for code rates 1/3, 7/15, and 2/3, respectively. It should be noted that these values are lower than the average TFS gain obtained using the Eq. (13.5), which is 3.9 dB. The optimum code rate with TFS is linked to the quality of the channels in order to obtain the best trade-off between robustness and capacity. For example, in the figure we can see that QPSK 7/15 with TFS achieves a similar performance to QPSK 1/3 without TFS.

Influence of Rotated Constellations in the TFS Performance

In this section, the performance of TFS is evaluated together with two-dimensional (2D) rotated constellations for two different code rates (1/3 and 2/3). The number of RF channels in the transmission has been set to three. One channel is attenuated with respect to the others by -6 dB and -12 dB. Fig. 32 depicts the results of the simulations with and without rotated constellations. The solid curves refer to the performance of the TFS transmission and the dotted curves represent the performance of the attenuated RF channel.

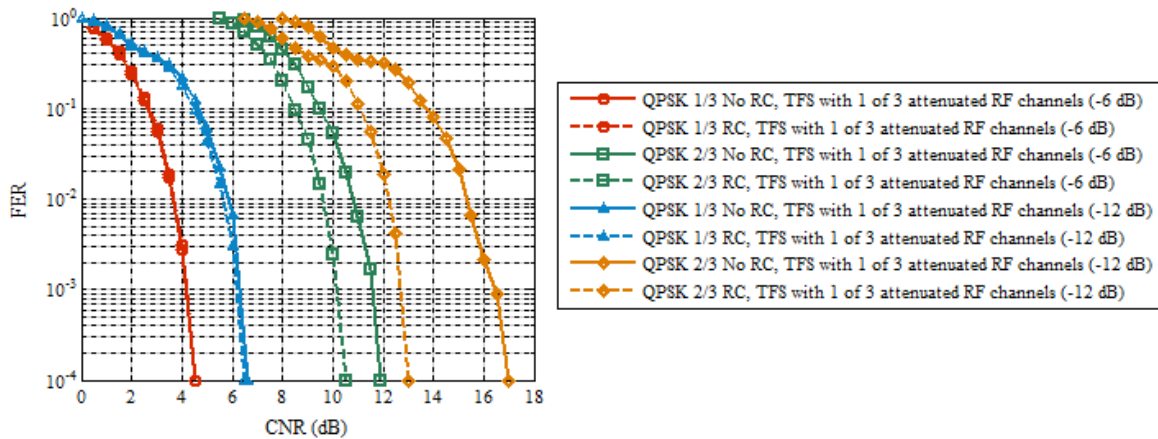


Figure 32: Simulated TFS performance with and without 2D rotated constellations with different code rates. TFS multiplex with three RF channels, and one of them attenuated with respect to the other two.

In the figure it can be seen that there is no gain with rotated constellation for a code rate 1/3, whereas there is a noticeable gain for a code rate 2/3. This is consistent with the potential gain of rotated constellations without TFS, providing its maximum gain for low order constellations and high code rates [11].

Although there is some dependence with the code rate, the important parameter is the amount of erasures in comparison with the redundancy percentage. Using e.g. code rate 1/2 (50% redundancy), the required CNR will necessarily approach infinity without rotated constellations when the percentage erasures approach 50%. Note that anything else is theoretically impossible. This is applicable to a situation with two RF channels, with one being erased. Rotated constellations, on the other hand, will however have only a limited penalty in this situation, so there is an infinite gain in such circumstances. Although it may not be so common to have full erasures, there may be very large differences in the signal strength between two RF channels, so there will be a big gain also in practice when one RF channel is much attenuated. With more RF channels, we may have the same reasoning, e.g. with code rate 1/3 and RC it is in principle cope with up to 67% (2/3) of erasures, but again this will necessarily require an infinite CNR with non-RC. In general, when the proportion of erasures approach (or even exceed) the percentage of redundancy of the FEC code RC will always show a big gain in comparison with non-RC.

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ANNEX: DETAILED ANALYSIS OF THE TFS GAIN FROM FIELD MEASUREMENTS

Analysis of the TFS gain with the number of RF channel is done by means of calculating it for 2, 3 and 4 RF channels assuming all the possible combinations of frequencies independently of their channel spacing. Average and standard deviation values are presented in **Fel! Hittar inte referenskälla**. Table 1. Globally, results throw an increase of the TFS gain with the number of RF channels in transmission. In general, the gain provided by 4 RF channels is greater than the same for 3 and 2 channels.

Table 1. TFS gain calculations for 2, 3 and 4 RF channels.

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	4-RF	3-RF	2-RF	@ 0 dB			@ 10 dB			@ 20 dB		
				4-RF	3-RF	2-RF	4-RF	3-RF	2-RF	4-RF	3-RF	2-RF
A	4.8	3.9	2.6	4.4	3.6	2.4	4.0	3.2	2.1	3.8	3.1	2.0
B	6.4	5.3	3.7	5.5	4.6	3.3	4.7	3.9	2.9	4.4	3.7	2.7
C	3.0	2.5	1.7	2.8	2.3	1.5	2.6	2.1	1.4	2.5	2.1	1.3
D	5.7	4.9	3.4	5.2	4.4	3.0	4.5	3.9	2.6	4.3	3.7	2.5
E	5.4	4.5	3.1	4.8	4.0	2.8	4.3	3.6	2.4	4.1	3.4	2.3
F	5.0	4.4	3.0	4.5	4.0	2.7	3.9	3.5	2.4	3.8	3.3	2.3

Another way to study the effect of the number of channels in the TFS gain is the calculation of the PDF for each transmitter area. In general, TFS gain for 3 and 4 RF channels resemble a Rayleigh distribution whereas for 2 RF channels it resembles an exponential distribution. That means that for 3 and 4 RF channels the probability of achieving some TFS gain in a location increases with respect to TFS with 2 RF channels. This effect can be shown in Figures 1-3 where PDFs are plotted.

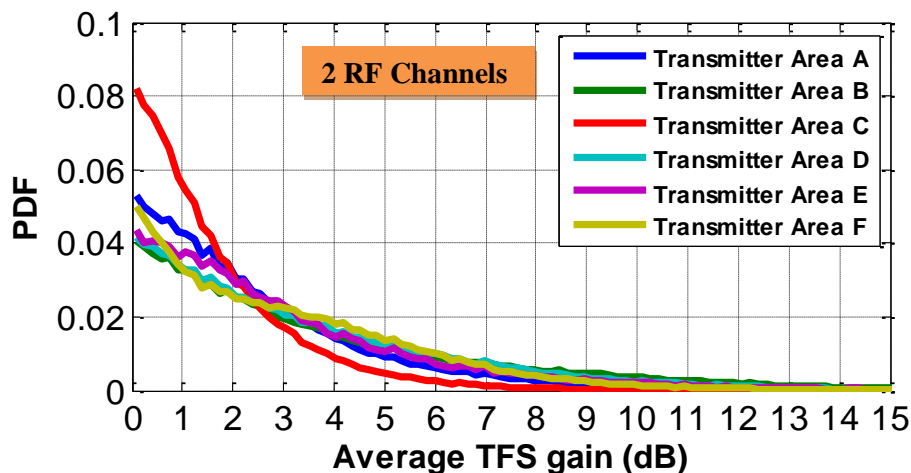


Figure 1. Probability density functions of the TFS gain for 2 RF channels. All the transmitter areas are considered.

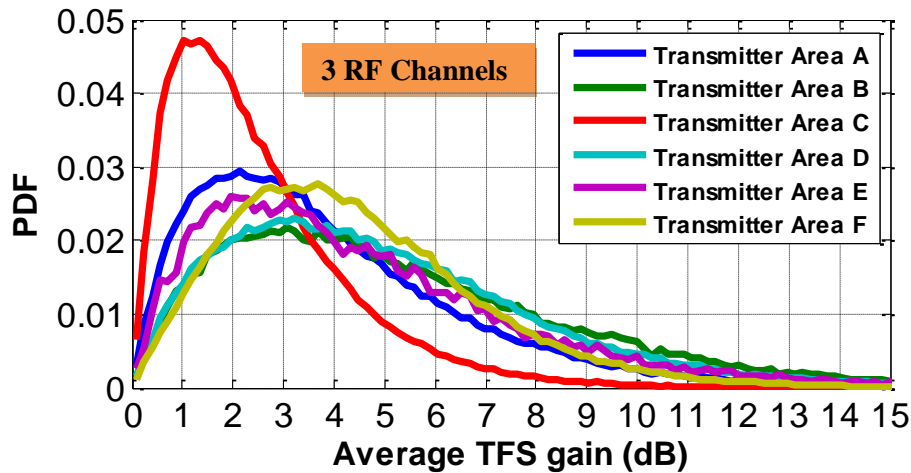


Figure 2. Probability density functions of the TFS gain for 3 RF channels. All the transmitter areas are considered.

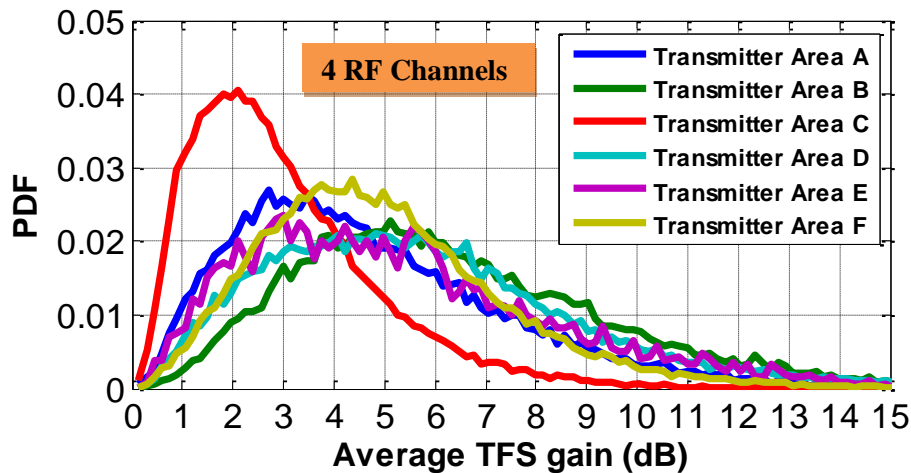


Figure 3. Probability density functions of the TFS gain for 4 RF channels. All the transmitter areas are considered.

As said, the study above was done considering a global combination of RF channels; however, it would also be very important to evaluate the effect of the number of RF channels and the frequency spacing together assuming different network configuration. For this purpose the measurements of each transmitter areas are studied as they represent a real DTT multiplexes allocation.

The frequency allocation of each RF channel is depicted in Table 2. According to each particular allocation, some different scenarios may be considered in analysis characterized by the spread of the channels in the band and their location inside the UHF band.

From these 6 different frequency distributions, three kinds of representative scenarios may be studied. The first one consists of a frequency allocation in which 4 RF channels are allocated in a particular region of the UHF band (e.g Outdoor A, in the low, and Outdoor C, in the mid parts of the band). The second scenario consists of a group of multiplexes which are spread over the band (this is the case for Outdoor D and

Outdoor E). The third scenario may consist of the bundling of some RF channels which have large spacing from another one (e.g Outdoor B and Outdoor F).

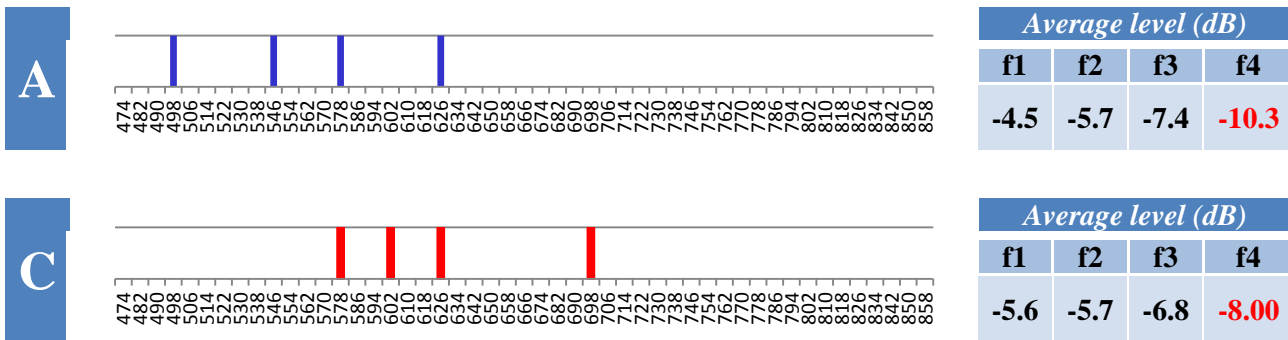
Table 2. TFS gain calculations for 2, 3 and 4 RF channels.

Location	Frequencies (MHz)			
Outdoor A	498	546	578	626
Outdoor B	514	722	754	786
Outdoor C	578	602	626	698
Outdoor D	474	530	674	730
Outdoor E	562	618	682	754
Outdoor F	594	674	786	802

For each set of measurements a table with the average level and the distribution of the multiplexes inside the UHF band are shown as this information may be interesting to understand the results obtained. TFS gain is also computed and shown in another table. The most significant values and results for each location are shown in red.

Locations Outdoor A and Outdoor C (Table 3) presents 4 RF channel allocated in the low and the mid areas of the UHF band, respectively. Multiplexes in A are uniformly distributed, with similar frequency spacing among them, that leads to an average power increase of around 2-3 dB from channel to channel whereas in C there exist one multiplex with a higher spacing and two of them have similar signal level as a result of the narrow spacing among them. The worst RF channel corresponds to f4, as expected.

Table 3. Average received signal strength with different spectrum allocations.



With this, the TFS gain (Table 4) tends to be almost the same for each RF channel bundling which maintains the highest spacing (f1-f4). The number of RF channels does not greatly affect the TFS gain; however gain increases with the channels with high level. The TFS gain performance for this location is the same as for the previous one. In particular for C, as f1 and f2 have similar level the RF channel combinations involving these two RF channels are not as large as other combinations. This reveals the importance of the RF channel spacing in the obtaining of high values of TFS gain.

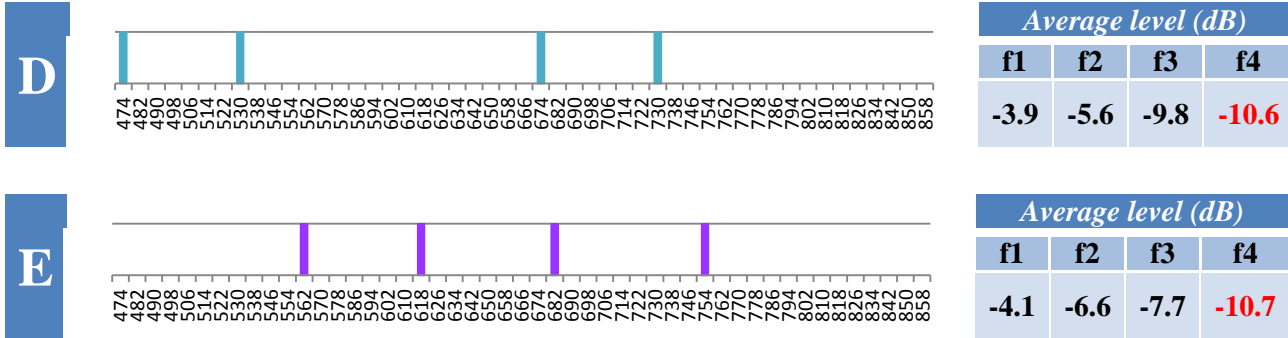
Table 4. TFS gain the different allocations.

		f1-f2-f3-f4	f1-f2-f4	f1-f3-f4	f2-f3-f4	f1-f2-f3
A	TFS gain (dB)	4.8	4.9	4.4	3.6	2.7

C	TFS gain (dB)	3.0	2.0	2.8	2.7	2.4
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Locations Outdoor D and E present 4 RF channels which are widely spread over the UHF band. Multiplexes in Outdoor E are uniformly distributed and the level of each one increases with frequency.

Table 5. Average received signal strength with different spectrum allocations.



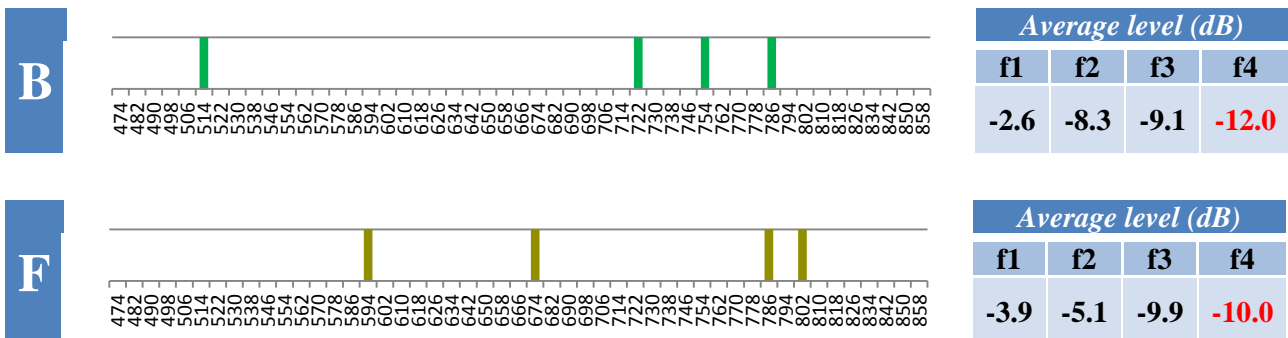
The resultant TFS gain is almost the same for both locations considering the maximum spacing (combinations involving f1-f4). TFS gain presents its large values with these combinations with independence of the number of RF channels. Gain does not present large variations if the spacing among multiplexes is constant.

Table 6. TFS gain the different allocations.

		f1-f2-f3-f4	f1-f2-f4	f1-f3-f4	f2-f3-f4	f1-f2-f3
D	TFS gain (dB)	5.7	5.6	5.3	4.1	4.8
E	TFS gain (dB)	5.4	5.4	5.2	3.7	3.6

The last two locations (Outdoor B and F) present the most irregular RF channel distribution. Both have 4 RF channels; however in B one multiplex is allocated in the low part of the band and has a large spacing to the other 3 which are in the up band. In F, two multiplexes are quasi-adjacent and therefore have a similar signal level.

Table 7. Average received signal strength with different spectrum allocations.



The results for these two locations present large TFS gain when combining the channels with the highest spacing. In particular for B gain increases when considering f1 whereas it has low values for combinations

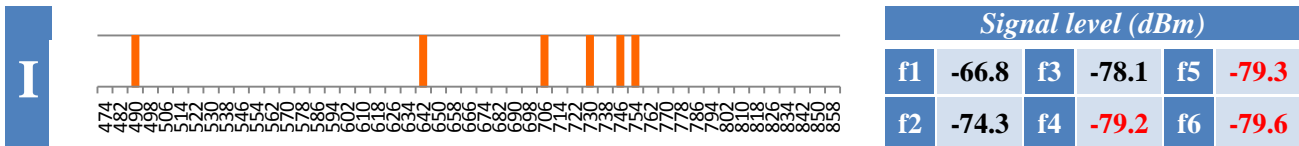
within the three other RF channels. Low frequency channels provide the largest values of TFS gain independently of the number of channels. For F, the combinations of adjacent channels do not provide high gain as these have a similar signal level.

Table 8. TFS gain the different allocations.

		f1-f2-f3-f4	f1-f2-f4	f1-f3-f4	f2-f3-f4	f1-f2-f3
B	<i>TFS gain (dB)</i>	6.4	6.7	6.6	3.1	4.6
F	<i>TFS gain (dB)</i>	5.0	5.0	4.4	3.5	4.8

To complete the analysis, indoor measurements are also computed considering all the frequencies which have been measured. Frequency allocation is not uniform (see Table 8) and thus signal level is almost the same for 4 of the 6 multiplexes. The differences in level come from 2 of them (f1 and f2).

Table 14. Average received signal strength with different spectrum allocations.



It is expected that the main contributions for the TFS gain would probably come from the 2 channels with high level, as shown in Table 9.

Table 9. TFS gain with the RF channels allocation in the indoor measurement campaign.

		f2-f3-f4-f5-f6	f1-f3-f4-f5-f6	f3-f4-f5-f6	f1-f4-f5-f6	f4-f5-f6	f1-f5-f6	f5-f6	f1-f6
I	<i>TFS gain (dB)</i>	3.5	6.7	2.4	7.4	2.0	8.1	1.4	9.0

The study on the spectrum allocations and TFS reveals that it is important to consider the channel spacing among RF channels (and in particular the maximum spacing between two of them) in order to obtaining the highest TFS gain as possible. However, an important issue that may be highlighted is that the achievement of large values of TFS gain does not imply the maximum levels of coverage as those RF channels situated in the low frequencies of the UHF band would probably achieve greater values of coverage (large signal level) that the RF channels situated in the high part of the band.