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Time Frequency Slicing for Future Digital Terrestrial Broadcasting Networks

Jordi Joan Giménez, David Gómez-Barquero, Staffan Bergsmark and Erik Stare

***Abstract*—Time Frequency Slicing (TFS) is a novel transmission technique for the future of terrestrial broadcasting. TFS breaks with the traditional transmission of TV services over single RF channels. With TFS, services are distributed across several channels by frequency hopping and time-slicing. The bundling of several RF channels into a TFS multiplex provides important advantages. A capacity gain is obtained due to a more efficient statistical multiplexing (StatMux) of video content since more services can be encoded in parallel. Improved frequency diversity also provides a coverage gain since signal imbalances between RF channels can be smoothed. Enhanced robustness against static and time varying interferences can also be achieved. TFS was described, although not implemented, for DVB-T2 and was fully adopted in DVB-NGH. At present, it is proposed for a future evolution of DVB-T2 and will also be considered in the ongoing ATSC 3.0 standard. This paper investigates the potential advantages of TFS by means of field measurements as well as simulations and discusses practical implementation aspects and requirements regarding transmission and reception. Results demonstrate the interesting advantages of TFS to improve both coverage and spectral efficiency, which addresses the future necessity of a more efficient DTT spectrum usage.**

***Index Terms*—terrestrial broadcasting, frequency diversity, field measurements, coverage gain, statistical multiplexing**

I. INTRODUCTION

DIGITAL terrestrial TV is the primary means of delivering TV services in many countries since it can provide near-universal coverage for fixed reception (and also for portable and mobile reception) to a potentially unlimited number of users. However, terrestrial broadcasting is in the spotlight of many spectrum authorities and the mobile communications industry [1]. Fixed and wireless broadband is rapidly growing and demanding higher spectrum shares [2]. The pressure of this demand is being felt globally by the broadcast industry since it is a large consumer of spectrum and therefore targeted for either significant improvement or replacement. In fact, many countries are currently allocating wireless broadband services in parts of the UHF band (e.g 790–862 MHz in ITU (International Telecommunications Union) regions 1 and 3 and 698–862 MHz in region 2) as a result of the bandwidth surplus after the analogue to DTT transition (digital dividend [3]). Important decision will also take place in the ITU World Radiocommunication Conference 2015 to consider additional spectrum allocations in the 694–790 MHz band in Region 1 (the so-called second digital dividend). DTT operators and broadcasters are now facing the scarcity of the valuable spectrum as a problem to address the massive push for new digital high quality content such as full migration to High Definition Television (HDTV) or even Ultra HDTV that needs of additional capacity requirements.

In this framework, broadcasting standardization bodies have initiated the study of new technical approaches to evolve its standards. ATSC (Advanced Television Systems Committee) has published a call for technologies for an ATSC 3.0 standard, ISDB (Integrated Services Digital Broadcasting) is evolving its terrestrial standard to ISDB-T2 and DVB (Digital Video Broadcasting) has initiated a study mission aimed at discussing new technologies for a future evolution of the DVB-T2 (Terrestrial 2^{nd} generation) standard [4]. In addition, the FoBTV (Future of Broadcast Television) initiative has also recognized the importance of a future digital terrestrial television system that could exploit the optimum combination among large coverage, large capacity and efficient use of the scarce spectrum from a global approach [5]. New techniques such as MIMO (Multiple Input Multiple Output) [6], Cloud Transmission (CloudTxn) [7] or Time Frequency Slicing (TFS) [8] are being studied and proposed as the most important technologies for the future of terrestrial broadcasting.

TFS consists in transmitting the digital TV services across several Radio Frequency (RF) channels by means of time-slicing and frequency hopping (i.e., discontinuous transmission of the services using multiple RF channels). TFS breaks with the tradition of transmitting TV services over single and independent RF channels. Whereas traditional reception is simply performed by tuning the RF channel which carries the desired service, with TFS, services are sequentially and discontinuously transmitted over hundreds of MHz (into a big TFS multiplex) in the broadcasting bands.

Figure 1 depicts the differences between the transmission of four services in the traditional way (each multiplex in a different RF channel) and by means of TFS over four RF channels. Reception with TFS is performed by dynamically tuning the RF channel that carries the time-slice of a particular service.

TFS was originally proposed and informatively specified within the standardization process of DVB-T2 [4] and was fully adopted in the mobile broadcasting standard DVB-NGH (Next Generation Handheld) [9] [10]. But the concept of TFS may be applied to any other new terrestrial broadcasting standard since it defines a physical layer technique. The future DTT standards could benefit from the advantages of TFS

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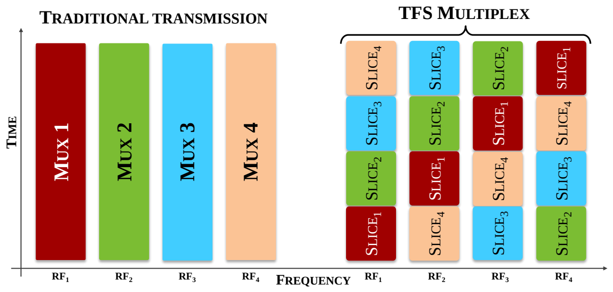


Fig. 1. Traditional digital TV transmission with 4 multiplexes over 4 RF channels (left) and TFS transmission with a TFS multiplex of 4 RF channels (right).

from different points of view: a capacity gain (in number of services – not actual bit rate) due to improved statistical multiplexing (StatMux) for Variable Bit Rate (VBR) services, a coverage gain due to improved frequency diversity and increased robustness against co-channel interferences (CCI).

Capacity gain is achieved when using StatMux with VBR services since it is possible to jointly allocate a larger number of services over the available bandwidth for TFS. Increased frequency diversity provides a coverage gain in noise-limited scenarios to cope with existing imbalances among the received signal strength from different RF channels. Whereas in a traditional DTT network some users may experience partial reception of the complete service offer, with TFS the coverage of the complete service offer may remain constant. TFS can also improve transmission robustness against signal time variations and tolerance against static and time varying interferences. Thanks to the frequency interleaving across several RF channels, depending on the error correction capability of the system, one, or even several, of the RF signals could be completely lost provided that the other RF signals are good enough [11]. This additional diversity may also be very interesting when time diversity cannot be exploited (e.g for pedestrian mobile reception).

TFS implementation in a DTT system requires compliance with certain issues such as scheduling and framing to ensure sequential tracking of the hops between RF channels and the even distribution of the services among them. Technical limitations such as tuning time at the receiver may also be considered. This paper presents the characteristics of TFS in the context of the future generation of terrestrial broadcasting, discusses its implementation in DTT networks and analyses its main advantages according to studies based on field measurements and simulations results. The paper is organized as follows: Section II describes the main advantages of TFS in terms of capacity gain, coverage gain and robustness against interferences and presents illustrative results by means of field measurements and simulations; Section III deals with the features of the TFS transmission technique and explains the main implementation issues and requirements of TFS at both transmitter and receiver sides from a generic point of view. DVB-T2 and DVB-NGH particular implementation aspects are also covered in this section. Conclusions are exposed in Section IV.

II. TFS ADVANTAGES FOR FUTURE DTT NETWORKS

A. *TFS capacity gain for VBR services*

TFS can provide a capacity gain due to a more efficient StatMux. 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 which does not guarantee an optimum bandwidth usage. StatMux takes advantage of the fact that, for a given video quality, 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 [12]. The so-called StatMux gain is defined as the percentage reduction of the required bit rate compared to fixed bit rate encoding for a given quality. Performance of StatMux depends on the bandwidth of the transmission channel, the number of services that are multiplexed and the statistical properties of service traffics. Obviously, there is no gain for a single service, but the gain increases as a function of the number of services until there is a point where it saturates. In a traditional network, the number of StatMux encoded video streams is limited to the maximum capacity of a single RF channel. With TFS, encoding is made considering the capacity of all the RF channels in the TFS multiplex together. Thus, the number of video streams that can be jointly encoded is higher. Figure 2 illustrates the difference between CBR (Constant Bit Rate) encoding and VBR encoding with StatMux.

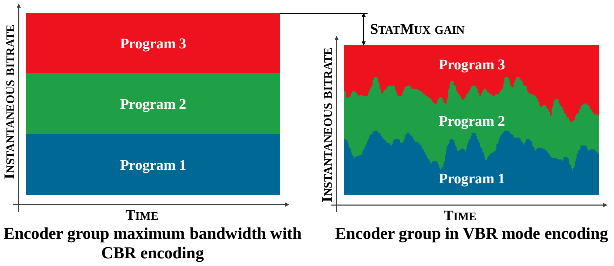


Fig. 2. Constant bit rate (CBR) encoding vs. Variable bit rate (VBR) encoding with statistical multiplexing (StatMux).

1) Illustrative Results: With MPEG-4/AVC video coding, the maximum StatMux gain for HDTV is reached when multiplexing 18 to 24 programmes, in which case the StatMux gain is about 32%, corresponding to a (virtual) capacity gain of 47% (1/(1-0.32) = 1.47). Table I collects this values, provided by Thomson [13].

TABLE I
STATISTICAL MULTIPLEXING GAIN WITH MPEG-4 AVC

Number of HD programmes	StatMux gain
1	0%
3-4	15%
9-12	30%
18-24	32%

Assuming that one RF channel could allocate around 3-4 HD programmes. The aggregation of 3 or 6 RF channels with TFS will lead to a StatMux gain of 21% ((1-0.15)/(1-0.3) = 1.21) and 25% ((1-0.15)/(1-0.32) = 1.25), respectively. Thus, the achievable gain in number of HD services ranges is 1-2 for the first case and 4-6 for the latter case.

The new HEVC standard [14], which is a likely candidate for coding with the future broadcasting standards, is expected to give similar performance regarding StatMux gain. Reduced bitrate for HD video (in the range of 50% for equal perceptual video quality) will probably reduce StatMux gain with TFS (large StatMux gain will already be exploited with 1 RF channel). However, 1080p HDTV and UHDTV video streams are expected to provide large StatMux gain with TFS with respect to allocation in a single channel.

B. TFS coverage gain in noise-limited scenarios

1) Received signal strength imbalances in the RF band: Transmitter stations are configured to use the same effective radiated power (ERP) per RF channel to transmit all the services in a DTT network. The signal of each RF channel is affected by different propagation conditions causing imbalances in the received signal strength from channel to channel at the same location. The imbalances between the RF channels in a DTT network are mainly linked to the frequency dependent characteristics of the physical elements of the transmission and reception chain (e.g. antenna radiation patterns, ground echoes, receiver noise figure, etc.) and propagation (e.g. reflection, material absorption, etc.) [15].

One of the sources for larger differences comes from antenna diagram on the large DTT stations. The antenna is required to cover all the used RF frequencies (e.g. the UHF bands IV/V in the range 470 MHz - 862 MHz). A compromise exists between bandwidth and smoothness of the antenna diagram. Most main stations have nominally, in the horizontal plane, omni-directional antenna diagrams. However, in practice, they are far from omni-directional [16] [17]. Even good antennas have variations in their antenna diagram in the order of 3 to 6 dB [15]. In addition, the diagrams also differ between frequencies as a function of the azimuth angle and sometimes very large notches appear for a certain direction and frequency.

Receiving antennas also suffer from frequency-dependent irregularities such as the antenna gain. Moreover, for network planning purposes a reference antenna with a constant antenna gain is used (e.g. 11 dB_d for UHF band [13]). Thus, the particularities of each receiver antenna are not taken into account when planning a network. In reality, gain is not constant and the received power at receiver input varies as a function of the frequency. The required field strength at the upper end of the UHF band is approximately 5 dB higher than at the low end to provide the same signal strength at the antenna output. The existence of a wide number of manufacturers made it difficult to know the real behaviour. In [18], the performance of 12 receiving antennas designed to operate in the UHF band is determined. Up to 4 dB gain variations are found on the same antenna for different frequencies and up to 7 dB gain variations are found comparing different antennas on the same frequency. Table II collects the main parameters that are taken into account at the receiver side [13].

TABLE II
FREQUENCY DEPENDENT PARAMETERS AT RECEIVER SIDE

Parameter	Rec. Value	Variation
Feeder loss	4 dB	$10log_{10}(f/f_R)$
Rx antenna gain	11 dB$_d$	$10log_{10}(f/f_R)$
Noise figure	6 dB	Depends on manufacturer
Effective antenna aperture	-4.6 dBm^2	$10log_{10}(\frac{1.64{\lambda_f}^2}{4\pi})$

Recommended values for f_R = 650 MHz (UHF bands IV/V) and rooftop reception for DTT, according to [13]. λ_f is the wavelength at frequency f

In addition, the noise figure of the receivers can also depend on the frequency. Measurements on receivers performed by Teracom, the Swedish DTT operator, have shown that the upper channel in many cases have increased noise figure. The measurements were obtained as part of performance verification of commercial DVB-T/T2 receivers from different manufacturers. Figure 3 presents the results of the measured noise figure of 4 different consumer DTT receivers.

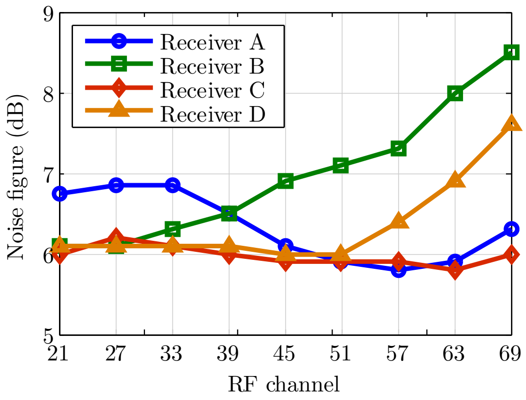


Fig. 3. Results from noise figure measurements on 4 commercial receivers.

In general, propagation attenuation also differs for different frequencies. In fact, local variations can be observed by moving the antenna through a few wavelengths [18] [19]. Terrain irregularities also affect propagation resulting in differences between the upper UHF channels and the lower. For standard terrain, the difference is in the order of 1-2 dB whereas in hilly areas the difference can be substantially larger.

Figure 4 shows the variations registered in 3 RF channels in the UHF band measured at the same time. Measurements are part of a campaign conducted by Teracom over different areas in Sweden. Relative level to the sum of the signal strength recorded for 4 frequencies is shown. SNR is calculated considering white noise in the band.

It can be seen that the RF channel that limits the coverage of the network is not always the same (e.g 730 MHz values are not always the lowest). Largest differences within these frequencies are around 10 dB.

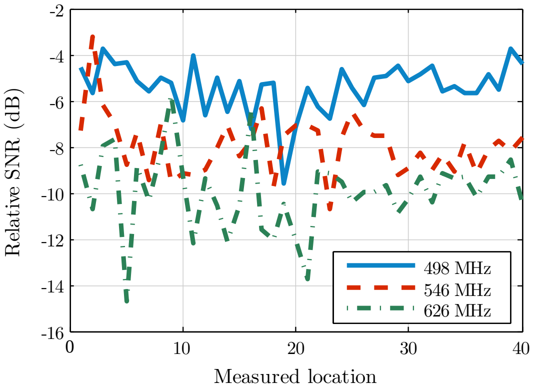


Fig. 4. Differences in the SNR level between 3 RF channels.

2) Definition and analysis of the TFS coverage gain: These effect of the signal imbalances between channels, added to the characteristics of digital reception (no chance for reception if SNR requirements are not met), make users get partial reception of the services in some situations. In a traditional DTT network, reception of the worst channel assures correct reception of all the multiplexes in the network. With TFS, on the contrary, the coverage is more likely to be determined by an effective SNR among all RF channels used in the TFS transmission [11] (only part of the data will be transmitted over the worst RF channel with TFS). According to this, the received signal (y_l) with TFS at a given period of time l can be modelled by:

$$y_l[m] = h_l x_l[m] + w_l[m], \quad m = 1, ..., T_c \tag{1}$$

where x_l is the transmitted signal, h_l is the channel impulse response of the period l, of duration T_c symbols, in which data is transmitted over a particular RF channel and w_l is the noise introduced at the receiver side. Assuming equal power (P) allocated to each RF channel, the maximum rate of reliable communication with TFS is given by:

$$S = \frac{1}{N_{RF}} \sum_{l=1}^{N_{RF}} log_2(1 + |h_l|^2 SNR_l), \quad bit/s/Hz \tag{2}$$

where SNR_l is defined as P/N_0, N_{RF} is the number of RF channels in the TFS multiplex and $|h_l|^2$ is the gain of the channel during l. By denoting the received SNR in an AWGN channel by $SNR = |h_l|^2 SNR_l$, an effective SNR (SNR_{eff}) that provides a rate that equals the average rate of the RF channels involved in the TFS transmission can also be derived from Equation 2 by:

$$SNR_{eff} = (\prod_{l=1}^{N_{RF}} (1 + SNR_l))^{1/N_{RF}} - 1 \tag{3}$$

Also note that for high SNR, SNR_{eff} is approximately equivalent to the average SNR of the RF channels, in dB scale.

The TFS coverage gain, G_{TFS}, is defined as the additional SNR provided by TFS over the SNR of the worst received RF channel in each location:

$$G_{TFS} = SNR_{eff} - min_i(SNR_i) \tag{4}$$

For the three RF channels shown in Figure 4, effective SNR and minimum SNR among them is calculated and depicted in Figure 5.

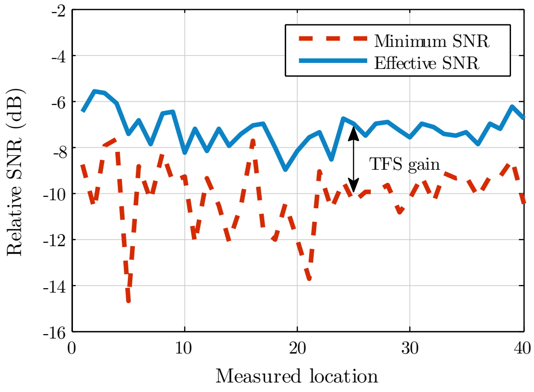


Fig. 5. Effective SNR and minimum SNR of the RF channels shown in Figure 4.

Coverage where all services are received is improved by frequency diversity. Global SNR of the RF channels with TFS is smoothed.

To better understand the concept of the TFS gain it should be taken into account that it is evident that the coverage of all services is higher than with independent RF channels in a traditional network. However, the coverage area of receiving at least one multiplex is somewhat reduced with TFS (e.g. the services allocated in the best received RF channel in a traditional non-TFS network will have more coverage than the same allocated with TFS). From the point of view of broadcasters and operators it is difficult to market DTT with significant different coverage of multiplexes in a given area. Consumers would neither understand to get a restricted set of services. Moreover, with the pay-TV model implemented in several countries, the whole service offer is delivered by means of several multiplexes which users expect to completely receive (as they pay for them). TFS gain is, thus, defined relative to the worst RF channel since with TFS all services are packed and delivered together.

3) Illustrative Field Measurement Results: The TFS coverage gain has been evaluated by means of field measurements. Measurements were performed for 6 different stations in Sweden which transmit DVB-T services with equal ERP. Received signal strength measurements around each station were obtained at 3 m height using an omni-directional antenna in order to acquire sufficient number of measurement data. For each service area a large number of samples (in the order of 40000 in each area) were measured for 4 different frequencies in a cyclic way (f_1, f_2, f_3, f_4, f_1, f_2,...). The measurements were originally made as coverage measurements for the regular DTT services in Sweden and were performed across large parts of the respective targeted coverage areas with large variations in terrain type within each area and with a majority of the measurements made in rural areas. Figure 6 shows the measurements routes around the transmitter close to the town Västervik. Other areas were measured in a similar way.

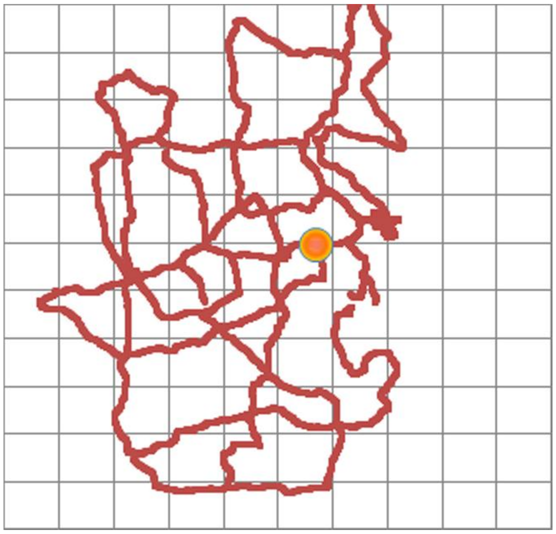


Fig. 6. Measurement routes within the transmitter area close to the town Västervik

Note that measurements are limited by sea on the eastern side. The measurements were calibrated to correspond to a constant receiving antenna gain across the UHF band. Thus, this measurements account for the frequency-dependent variations of the transmitter antenna diagram and propagation. Nominal frequencies of the RF channels measured in each area (1 to 6) are indicated in Table III. The TFS coverage gain calculated by Equation (4) over the different locations in each area for the 4 RF channels is shown in the last column.

TABLE III
FREQUENCIES MEASURED AND CORRESPONDING TFS GAIN

	f_1 (MHz)	f_2 (MHz)	f_3 (MHz)	f_4 (MHz)	G_{TFS} (dB)
1	498	546	578	626	4.6
2	514	722	754	786	6.0
3	578	602	626	698	2.9
4	474	530	674	730	5.5
5	562	618	682	754	5.1
6	594	674	786	802	4.8

It can be observed that the frequency spacing between channels and its distribution within the UHF band are different for the 6 areas. Results show that the TFS coverage gain increases with the frequency separation between the highest and lowest RF channels. The reason is that larger signal strength imbalance between RF channels is found for higher frequency separation [15]. TFS gain has also been computed for 2 and 3 RF channels for the same areas. It reaches its maximum values for those RF channels combinations which involve the most separated channels (e.g TFS gain for 2 RF channels, 594 and 802 for area 6, is 4.3 dB). Hence, the number of RF channels in the TFS multiplex is not a critical parameter for the TFS coverage gain for a given maximum frequency separation among two RF channels, but their distribution within the frequency band.

Figure 7 shows the empirical CDF (Cumulative Density Function) of the TFS coverage gain computed for the 6 areas. In average, the TFS gain for 50% of locations is around 4.5 dB. Moreover, TFS gain also reaches values around 10 dB for approximately a 10% of locations. In general, whereas for 2 channels the TFS gain resembles an exponential distribution, for 3 or more RF channels it resembles a Rayleigh distribution. The number of locations with no TFS gain is reduced when more channels are added to the TFS multiplex. TFS gain is expected to be even larger since frequency dependent characteristics of receivers are not taken into account in this measurements.

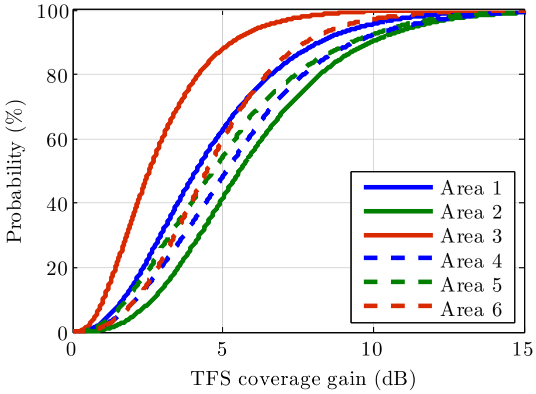


Fig. 7. Empirical CDF of the TFS coverage gain with 4 RF channels at the 6 different measured areas.

Measurements performed with 10 meter receiving antenna also confirm that the TFS Gain is on average very similar at 3 meter using an omni-directional antenna.

4) Illustrative Coverage Prediction Results: Computer simulation coverage predictions have been conducted to illustrate the effect of TFS with respect to a traditional DTT network. A transmitter station has been located at the top of the Aitana (1556 m above sea level), a mountain in the South-East of Spain which currently hosts one of the main DTT transmitters that serves the region. 4 RF channels are radiated (central frequencies are 474, 570, 650 and 770 MHz).

Transmitter antenna has been assumed an omni-directional panel antenna system with 4 panels fed with equal power (1 kW ERP). 4 different radiation patterns (one per RF channel) have been created, as depicted in Figure 8 to account for the frequency dependency of the antenna diagrams following the features of TV broadcasting antenna systems in [16]. Irregularities of the azimuth pattern are kept within ±1.5 dB (optimistic assumption).

A DVB-T2 signal (8 MHz, 32k extended, GI 1/128, 256-QAM, 3/5) is transmitted. Required C/N of this mode in Rician channel is 18.1 dB [13]. According to the reception parameters collected in Table II, minimum median equivalent field strength at 10 m above ground level is derived for each RF channel. Coverage is predicted to achieve reception in the 95% of locations and 99% of time for each RF channel for fixed rooftop reception. The propagation model is the widely used ITU Recommendation ITU-R P.1546 [20]. Figure 9

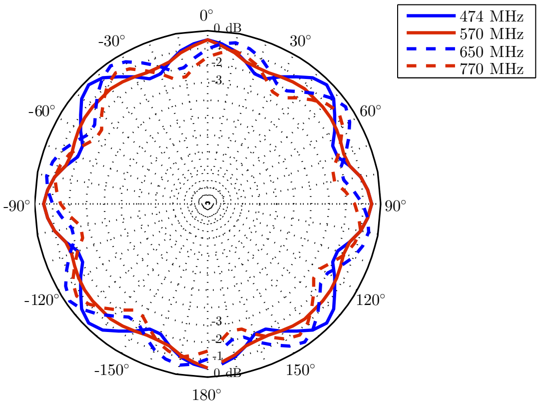


Fig. 8. Antenna radiation diagrams considered for coverage estimation.

depicts the coverage area of each RF channel according to the assumed conditions.

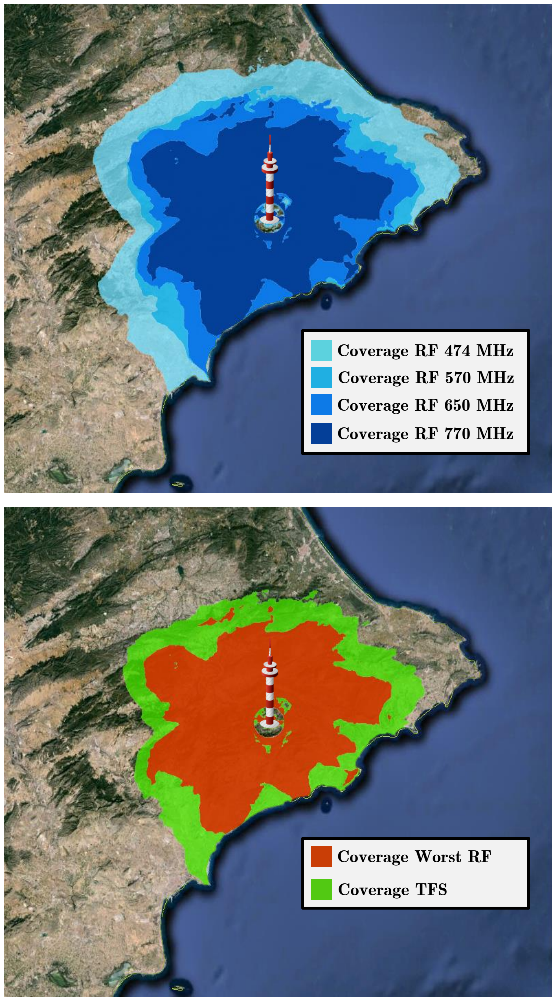


Fig. 9. Coverage area of 4 RF channels broadcast from a DTT station (above) and coverage area of the worst RF channel and coverage extension of the complete service offer area with TFS (below)

It can be seen that reduced coverage area is obtained when increasing frequency. Individual reception of at least 1 RF channel is possible in a wider area (around 3000 km^2), but reception of the complete service offer is, however, restricted to locations closer to the transmitter station (1350 km^2). Service area can be increased by 60% (2150 km^2) with TFS (see Figure 9).

5) Illustrative Simulation Results: Performance evaluation of TFS in real systems is studied by means of physical layer simulations with DVB-T2 and DVB-NGH transmission modes (SISO, 8 MHz, 8k, 1/4 64QAM). 4 RF channels (474 MHz 570 MHz 666 MHz 762 MHz) are considered with their corresponding average signal imbalance given by the model in [15]. Fixed rooftop reception (Rician F1 [21] channel) and mobile reception (TU6 channel [22], Doppler 80 Hz) are evaluated for the same interleaving duration ($T_{TI} = 200$ ms). Encoded data is evenly distributed (time-interleaved) among the 4 RF channels. Figure 10 illustrates the performance of TFS for different code rates are used.

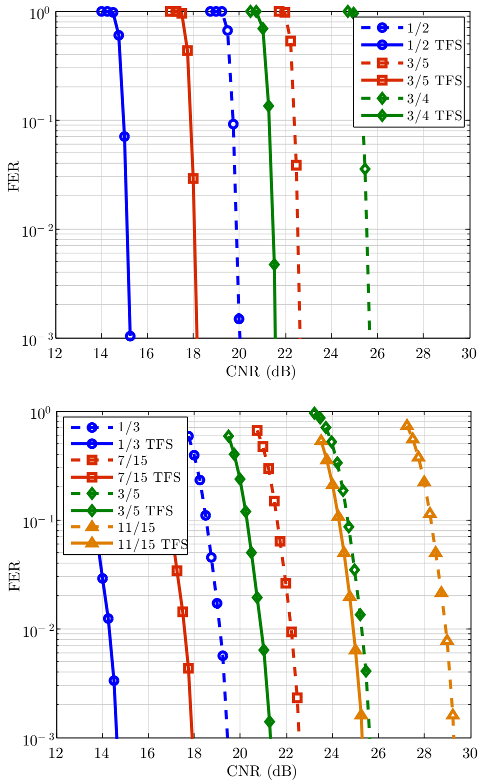


Fig. 10. Performance of TFS in the Rician F1 channel for 3 DVB-T2 modes (above) and the TU6 channel ($f_d = 80$ Hz) for 4 DVB-NGH modes (below). FER curves with 64QAM and different code rates according to the standards.

The results show the FER (Frame Error Rate) curves with 64QAM. The dashed lines represent the performance of the worst RF channel (the one with the highest imbalance with respect to the others). The difference between solid and dashed lines results in the TFS gain. In this case, the achievable gain is around 4.5 dB. Table IV shows the TFS gain for FER 10^{-3}. The gain depends on the error-correcting capabilities of the code rate. The gain of TFS increases when lower code rates are used since more data is recovered thanks to frequency diversity. Potential gain is slightly higher for mobile reception than fixed rooftop reception allowing increased robustness with TFS against channel variations. The additional frequency diversity is especially important for pedestrian reception conditions, where the time diversity is very little or non-existent. Moreover, for mobile reception the increased frequency diversity can reduce the requirements for time interleaving, reducing the end-to-end latency and zapping time.

TABLE IV
TFS GAIN AS FUNCTION OF THE CODE RATE

Mode	TFS gain	Mode	TFS gain
DVB-T2 Rice 1/2	4.8	DVB-NGH TU6 1/3	4.9
DVB-T2 Rice 3/5	4.5	DVB-NGH TU6 7/15	4.7
DVB-T2 Rice 3/4	4.1	DVB-NGH TU6 3/5	4.4
		DVB-NGH TU6 11/15	4.0

C. Robustness against interferences by TFS

From the interference point of view, TFS can also provide a gain as the interferences from other transmitters are usually frequency dependent and, thus, does not occur in all the channels in the UHF band at the same time. Such interference reduction can be exploited to improve the coverage in interference-limited areas, or to allow tighter frequency reuse patterns such that more networks can fit within a given spectrum [23].

The most important source of interference comes from stations broadcasting in the same RF channel (CCI). Frequency plans for terrestrial broadcasting (such as Geneva plan, GE06) 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.

The interfering signals coming from a digital TV transmitter look like Gaussian noise (AWGN) 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.

TFS may also be beneficial to reduce potential interferences caused by the deployment of 4G long term evolution (LTE) cellular services. LTE will use the upper part of the UHF band 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 [24]. 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 SNR thanks to the reception of the other parts. It should be noted that overloading may be prevented by applying a filter with high enough attenuation of the interfering LTE signal. In a non-TFS case there is a trade-off between the possible amount of attenuation that can be achieved and the acceptable amount of attenuation of the closest DTT RF channel. However, in the TFS case this trade-off is much less critical since one may accept quite high attenuation on the closest DTT RF channel (in some cases even total cancellation) provided the quality of the other RF channels are good enough to allow reception of the complete TFS multiplex.

1) Illustrative Simulation Results: Simulations have been conducted in order to evaluate the potential advantage of TFS against CCI from conventional MFN frequency reuse. A MFN was built by a regular hexagonal pattern. In the center of each hexagon identical and equidistant omni-directional transmitters are located. A certain frequency reuse factor N is defined to cover an arbitrarily large area. A total of 6 multiplexes are used per site, so that 6xN RF channels are required from the UHF band to build the DTT network. Figure 11 depicts the wanted and interferer transmitters in a network with N=7.

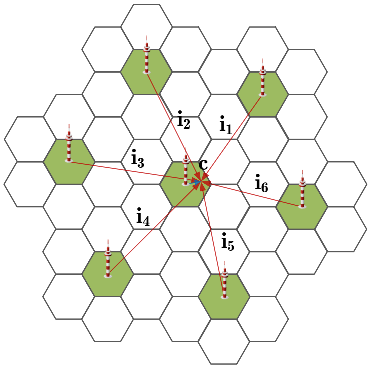


Fig. 11. Ideal MFN network in an hexagonal lattice. Each transmitter in the network is located at the central position of each hexagon. Co-channel transmitters are highlighted.

Signal-to-interference ratio (C/I) determines the maximum theoretical (Shannon) capacity that can be transmitted to a reception point. The normalized (b/s/Hz) Shannon channel capacity within the used channel is given by:

$$log_2(1 + \frac{C}{\sum_{j=1}^{M_{TX}} I_j}) \quad (5)$$

where M_{TX} is the number of co-channel transmitter considered.

Coverage is defined to require the reception of all transmitted services with 95% probability in the ”worst” point of the hexagon, i.e. the point with the lowest Shannon channel capacity. For non-TFS this means the lowest capacity value of all the RF channels and for TFS the average capacity among the used RF channels, which is higher. The propagation model used was the ITU-R P.1546 [20] for 50% of time for the wanted signal and 1% of the time (i.e. increased levels, pessimistic assumption) for the interfering signals (interference transmitters from 3 co-channel tiers are considered). Effective antenna height is 250 m, corresponding to typical values for central Europe. Reception was always assumed at 10 m above ground level with a directional antenna (ITU Recommendation ITU-R BT.419 [25]). Shadow fading is modeled as log-normally distributed (5.5 dB standard deviation) and 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).Effects of transmitting antennas frequency dependencies and wave propagation are modelled as an additional frequency-dependent fading of 2 dB, according to [15].

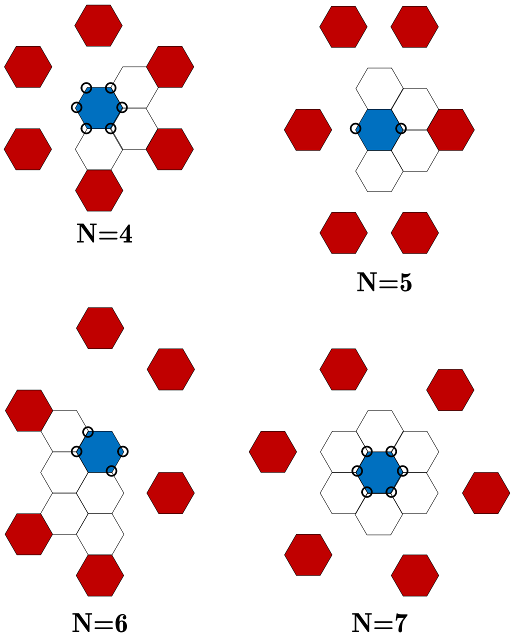


Fig. 12. Frequency reuse patterns and corresponding worst points for each configuration.

4 different ideal frequency reuse patterns are studied, see Figure 12. The worst points in the hexagon are also indicated for each configuration. Results for the absolute spectral efficiency for each configuration with and without TFS are depicted in Figure 13 for different inter-site distances (10 km to 100 km), which are in the range of the most common transmitter separation in DTT networks.

It can be seen that higher increased spectral efficiency is obtained with TFS for narrow frequency reuse patterns. The largest spectrum efficiency is obtained for N=4. Results also show that whereas with non-TFS spectral efficiency is limited by the strongest interferer (e.g with N=5 the nearest interferer is located at 3 times cell radius), TFS highly minimizes this effect (highest spectral efficiency increase is found for N=5). Note that in this simulations all interferers are assumed to reach the maximum interference at the same time. Gains in reality are, thus, expected to be higher.

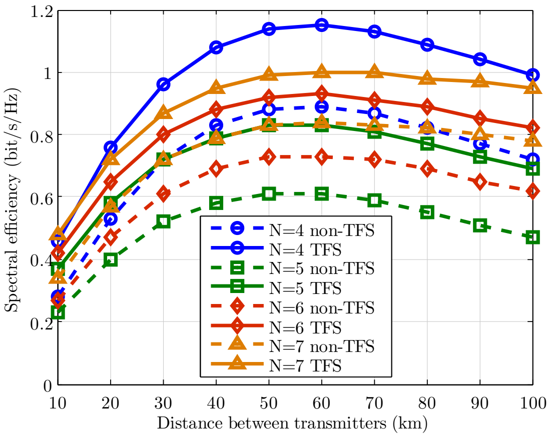


Fig. 13. Spectral efficiency as a function of the distance between transmitters and the frequency reuse patterns indicated in Figure 12.

III. IMPLEMENTATION ASPECTS OF TFS

A. *TFS Operation Modes*

Implementation of TFS at the transmitter stations in a DTT network is closely linked to the scheduling and framing characteristics of the system and the network scenario. How frequency and time diversity is exploited by TFS depend on them. The basic idea behind TFS is to ideally split the code-words of each transmitted service and spread them over time and frequency. Thus, received code-words will internally experience the effect of the different RF channels. Depending on the length of the physical frames on which the services will be allocated and how they are allocated in the RF channels, TFS can be operated intra-frame or inter-frame.

Intra-frame TFS operates internally within the same frame by means of frequency hopping between time-interleaved data slices (time-divided units of encoded data) of a service which are transmitted in different RF channels, as depicted in Figure 14. Hence, a frame containing slices of all the services is transmitted in each RF channel.

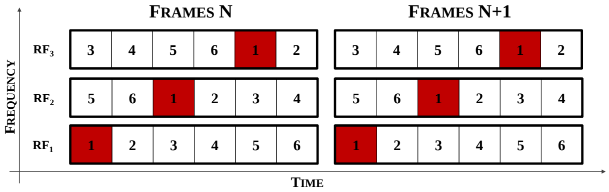


Fig. 14. Example of intra-frame TFS operation with frames transmitted over 3 RF channels and containing information of 6 services. Data slices of the same service are sequentially received by frequency hopping between the RF channels.

Intra-frame TFS allows for intra-frame and inter-frame time interleaving. With intra-frame time interleaving all the slices of a service within one frame are jointly interleaved in frequency and time. Intra-frame TFS allows to exploit both increased frequency and time diversity as well as enhanced statistical multiplexing.

Intra-frame TFS is suited for long frames as it 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 and the total amount of data in a frame. Increasing the number of RF channels also leads to lowering the time interval for frequency hopping.

Frame-by-frame operation (inter-frame TFS) is also possible by using frequency hopping only from frame to frame (e.g. at frame boundaries). With this, data of a particular service is totally transmitted in different RF channel during a frame, and frequency hopping is performed on a frame basis, see Figure 15.

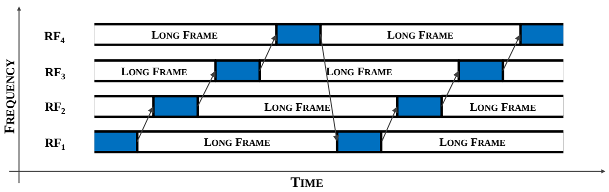


Fig. 15. Example of inter-frame TFS operation among short length frames over 4 RF channels. A given service is transmitted in a different frame and RF channel from frame to frame.

Inter-frame TFS is the only TFS operation mode possible for short frames. 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.

Although not implemented, TFS is described, as informative (annex E) in DVB-T2 standard [4], and as a fully operative technique in DVB-NGH standard. DVB-T2 frame structure consist of signalling (i.e. P1 symbols, L1 signalling) and data PLPs (Physical Layer Pipes) of type 0 (common), type 1 (1 slice per T2-frame) and type 2 (several slices per T2-frame). With TFS, intra-frame operation is performed with the slices of type 2 data PLPs which are distributed over all RF channels during one T2-frame. In this case, P1 symbols, L1 signalling and common PLPs are simultaneously available on each RF channel. Regarding type 1 data PLP, each one is transmitted in one T2-frame and over one RF channel. However, inter-frame TFS operation can be performed between type 1 data PLP if this is transmitted over a different RF channels. In DVB-NGH [9], inter-frame TFS operation is also defined across FEFs (Future Extension Frames) so that the services are allocated in such short-length frames on different RF channels.

B. TFS frequency hopping time at receiver side

A proper scheduling for intra-frame TFS guarantees frequency hopping internally in a frame with a single tuner. The major disadvantage of TFS in DVB-T2 is the requirement of two tuners at the receiver which makes them more complex and expensive. On the other hand new receivers integrating two tuners (e.g for MIMO operation) may be able to operate TFS without the concerns explained below.

Single tuner operation is feasible with a guard period between the last data slice in one frame and the first slice in the following frame to allow enough tuning time. The guard period can be achieved by the use of a short frame (e.g. using the FEF mechanism) between TFS frames or by using a sufficient number of Type 1 PLP symbols in the beginning of the frame.

Assuming an achievable tuning time around 5 ms without significantly increasing receiver complexity, the minimum frequency hopping time between two data slots is represented in Figure 16.

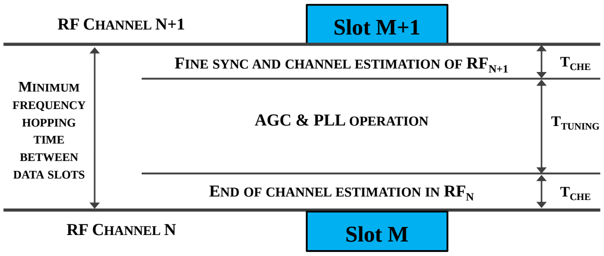


Fig. 16. Necessary timing for TFS frequency hopping reception with a single tuner.

It should consider the time required for fine frequency synchronization and channel estimation, T_{ChE}, of the previous RF channel (to finish interpolation over OFDM symbols) and the next one (to begin channel estimation), and the PLL (Phase Locked Loop) and AGC (Automatic Gain Control) tuning times T_{Tuning}. Hence, the minimum frequency hopping time between two data slots can be calculated as:

$$T_{FH_{min}} = 2T_{ChE} + T_{Tuning} \tag{6}$$

For example, in DVB-T2, for a typical mobile configuration for the UHF band with FFT 8K GI=1/4 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 16K 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).

This necessary time gap between slots from different consecutive RF channels must be taken into account both in scheduling of intra-frame and inter-frame TFS data slots as well as at frame boundaries.

C. Data scheduling at transmitter side

At transmitter side, it must be assured that receivers can follow the TFS transmission with a single tuner. A correct scheduling of the data from each service is also necessary in order to exploit the combined frequency and time diversity. Ideally, encoded data should be uniformly distributed among all RF channels and properly spread in time. This allows well received parts of data to compensate for a badly received parts. The number of data slices must be an entire multiple of the number of RF channels to guarantee correct frequency hopping. It should be noted that the different RF channels must be synchronized such that the receivers can perform frequency hopping between data slices in a sequential way in order to recover the complete data of the service. An illustrative example of the scheduling for intra-frame TFS is depicted in Figure 17.

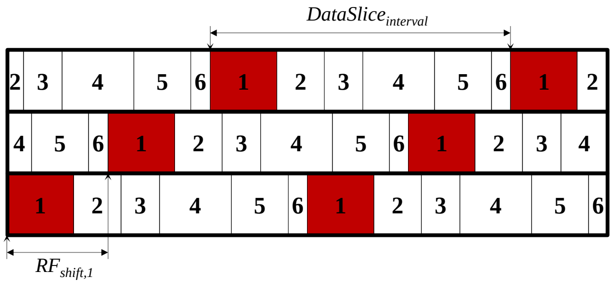


Fig. 17. Resultant data scheduling for intra-frame TFS.

Data from services (6 in the example) is divided into data slices (in this case 2). This division establishes the so-called $Subslice_{Interval}$, which is the time interval (or number of data units) between two consecutive data slices of the same service in the same RF channel:

$$DataSlice_{Interval} = \frac{ServiceData}{N_{slices}} \tag{7}$$

where $ServiceData$ is the total data of the services, and N_{slices} represents the total number of slices which depends on the number of RF channels and the number of slices in each one.

Even distribution of the data is assured by $RF_{Shift,i}$, applied to the slices from channel to channel:

$$RF_{Shift,i} = i\frac{DataSlice_{Interval}}{N_{RF}}, \qquad i = 1, 2, ..., N_{RF} - 1 \tag{8}$$

where N_{RF} is the number of RF channels. According to Figure 17 with 3 RF channels, this means that the shifting between the slices transmitted in RF channel 1 and RF channel 2 is given by $RF_{Shift,1}$, and $RF_{Shift,2}$ between RF channels 2 and 3. This operation also prevents from overlapping of the slices of the same service in different RF channel.

Inter-frame TFS operation across short frames relaxes data scheduling since it allows longer time intervals for frequency hopping. Although timing is less critical for inter-frame TFS, a trade-off between the convenient time interleaving and zapping time must be reached.

Zapping time involves the inevitable delay produced when a user receiving a particular service decides to switch to a different service carried on another stream as the new service cannot be presented immediately to the user. The main factor that involves zapping time performance is the interleaving depth which is linked to the TFS cycle time (the time interval between the reception of two consecutive data slices in the same RF channel). For intra-frame TFS with intra-frame time interleaving, the average zapping time is 1.5 times the TFS cycle time (one and a half frame) 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 signalling parameters and to receive the time-interleaved data contained in the frame). For inter-frame TFS it mainly depends on the time interleaving depth. The TFS zapping time for this important use case is therefore the same as for non-TFS.

Different solutions for scheduling of the short frames in inter-frame TFS are presented in Figure 18.

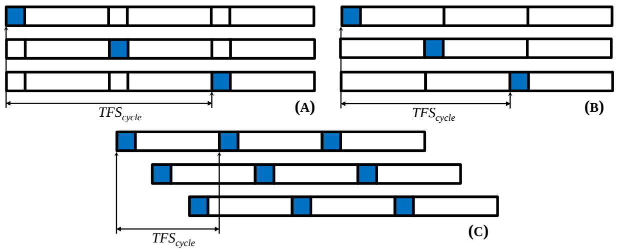


Fig. 18. Inter-frame TFS using co-timed frames (a), time-shifted frames but co-timed super-frames (b) and time-shifted super-frames.

Although the first two schemes (a and b) 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 (c).

For the latter case, TFS cycle time (TFS_{cycle}) must meet the following equation:

$$N(S_{length} + G_{length}) = S_{length} + kFrame_{length} \tag{9}$$

where N is the number of interleaved short frames, S_{length} is the length of a short frame, G_{length} is the gap for frequency hopping, and $Frame_{length}$ is the length of the normal frames. k is the number of normal frames between short frames.

TFS cycle time for inter-frame TFS mainly depends on the spacing among short frames and how data is interleaved across them. In general, zapping time increases with the spacing among short frames. However, large spaced short frames increase time interleaving which also increases time diversity.

D. Regulatory framework with TFS

The introduction of TFS will require legislation modifications in some countries to implement the network in the optimum way, i.e, to pack all services together (to exploit StatMux gain) and to spread them across different RF channels (to improve RF performance) or even between different bands (e.g. UHF/VHF). Traditionally, a broadcasting licence holder is the holder of an RF channel (e.g. in analogue TV one service is transmitted over one RF channel). The introduction of digital terrestrial television has already required an adaptation of the legal framework governing broadcasting licensing in many countries so that one frequency (multiplex) is shared by several broadcasters [26]. The implementation of TFS may take into account for a complete separation between contents (broadcasters) and transmission (operators).

IV. CONCLUSIONS

TFS offers potentially better RF performance by transmitting TV services across several RF channels by means of frequency hopping and time slicing. In addition to a potential capacity gain due to enhanced StatMux (e.g. up to 25% for 6 RF channels and HD content), TFS can provide very important coverage gains (around 4.5 dB for TFS 4 RF channels multiplex according to field measurements) for both fixed rooftop and mobile reception conditions. The implementation of TFS will increase the reliability of the DTT network and the quality perception of the users since global reception of the services is enhanced in the service area. When there are large variations in signal strength between different RF signals the good RF channels tend to compensate for the bad ones. TFS can also considerably improve the robustness against interferences. Spectral efficiency with TFS may also be improved by reducing frequency reuse patterns. 20% to 40% spectral efficiency increase is obtained for different patterns for transmitter distances around 60 km to 80 km. TFS could also deal with LTE interferences in the UHF band.

TFS would be fully compatible with other transmission techniques such as MIMO. In addition, TFS transmission may also benefit from the frequency and directional variations of the cross-polar antenna diagrams by smoothing the negative effects of such variations. An appropriate data scheduling in the broadcasting system will guarantee the correct reception of the services and the distribution of data across the RF channels. Configuration flexibility to operate within and among frames will also allow an optimum exploitation of the advantages of TFS. However, new regulation approaches, in the basis of licensing capacity instead of frequencies, are required for an optimum implementation of TFS in the broadcast bands. Operators should also take into account the requirements involving delivery and distribution networks for the adaptation of the existing DTT deployments to provide services by TFS.

REFERENCES

[1] "The Future of Terrestrial Broadcasting," EBU, Tech. Rep. 013, November 2011.

[2] "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012–2017," 2013.

[3] "Digital dividend: Insights for spectrum decisions," ITU, Tech. Rep., 2012.

[4] *Frame structure channel coding and modulation for a second generation digital terrestrial television broadcasting system (DVB-T2)*, ETSI Std. EN 302 755, Rev. V1.3.1, April 2012.

[5] P. Macavock, "Grand Aspirations," *EBU Tech-i Magazine*, no. 16, June 2013.

[6] D. Vargas, D. Gozalvez, D. Gomez-Barquero, and N. Cardona, "MIMO for DVB-NGH, the next generation mobile TV broadcasting," *IEEE Commun. Mag.*, vol. 51, no. 7, pp. 130–137, 2013.

[7] Y. Wu, B. Rong, K. Salehian, and G. Gagnon, "Cloud transmission: A new spectrum-reuse friendly digital terrestrial broadcasting transmission system," *IEEE Trans. Broadcast.*, vol. 58, no. 3, pp. 329–337, 2012.

[8] J. Giménez, D. Gómez-Barquero, S. Bergsmark, and E. Stare, "Time-Frequency Slicing (TFS) for DVB-NGH," in *Next Generation Mobile Broadcasting*, D. Gómez-Barquero, Ed. CRC Press, 2013, ch. 13, pp. 389–416.

[9] *Next Generation broadcasting system to Handheld, physical layer specification (DVB-NGH)*, Digital Video Broadcasting Std. DVB Bluebook A160, November 2012.

[10] D. Gómez-Barquero, Ed., *Next Generation Mobile Broadcasting*. CRC Press, March 2013.

[11] M. Makni, J. Robert, and E. Stare, "Performance analysis of time frequency slicing," in *Electronic Media Technology (CEMT), 14th ITG Conference on*, 2011, pp. 1–6.

[12] M. Rezaei, I. Bouazizi, and M. Gabbouj, "Statistical Time-Frequency Multiplexing of HD Video Traffic in DVB-T2," *International Journal of Digital Multimedia Broadcasting*, vol. 2009, p. 12, 2009.

[13] "Frequency and network planning aspects of DVB-T2," European Broadcasting Union, Tech. Rep. 3384, Nov 2013.

[14] G. Sullivan, J. Ohm, W.-J. Han, and T. Wiegand, "Overview of the High Efficiency Video Coding (HEVC) Standard," *Circuits and Systems for Video Technology, IEEE Transactions on*, vol. 22, no. 12, pp. 1649–1668, 2012.

[15] J. Giménez, D. Gozalvez, D. Gómez-Barquero, and N. Cardona, "Statistical model of signal strength imbalance between RF channels in DTT network," *Electronics Letters*, vol. 48, no. 12, pp. 731–732, 2012.

[16] "Transmitting antenna characteristics at VHF and UHF," ITU, Recommendation ITU-R BT.1195-1, 2013.

[17] H. Kawakami, "A Review of and New Results for Broadband Antennas for Digital Terrestrial Broadcasting: The Modified Batwing Antenna," *Antennas and Propagation Magazine, IEEE*, vol. 52, no. 6, pp. 78–88, 2010.

[18] "Radiation pattern characteristics of UHF television receiving antennas," ITU, Tech. Rep. ITU-R BT.2138.

[19] Y. Oda, R. Tsuchihashi, K. Tsunekawa, and M. Hatay, "Measured path loss and multipath propagation characteristics in UHF and microwave frequency bands for urban mobile communications," in *Vehicular Technology Conference, 2001. VTC 2001 Spring. IEEE VTS 53rd*, vol. 1, 2001, pp. 337–341 vol.1.

[20] "Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3 000 MHz," ITU, Recommendation ITU-R P.1546-4, 2009.

[21] *Implementation guidelines for a second generation digital terrestrial television broadcasting system (DVB-T2)*, ETSI Std. TS 102 831, Rev. V1.2.1, August 2012.

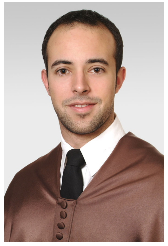
[22] H. Himmanen, "Studies on channel models and channel characteristics for mobile broadcasting," in *Broadband Multimedia Systems and Broadcasting, 2008 IEEE International Symposium on*, 2008, pp. 1–9.

[23] E. Stare, "Improved spectral efficiency by time-frequency slicing and advanced network planning," in *International Broadcasting Convention (IBC)*, 2013.

[24] G. Baruffa, M. Femminella, F. Mariani, and G. Reali, "Protection ratio and antenna separation for DVB-T/LTE coexistence issues," *Communications Letters, IEEE*, vol. 17, no. 8, pp. 1089–7798, 2013.

[25] "Directivity and polarization discrimination of antennas in the reception of television broadcasting," ITU, Recommendation ITU-R BT.419-3, 1990.

[26] E. Machet, "Plenary Session 2: Regulatory and Licensing Models for DTT Summary of the answers to the questionnaire ," in *32nd EPRA Meeting, Belgrade*, 2010.



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David Gómez-Barquero received the double M.Sc. degree in telecommunications engineering from the Universitat Politècnica de València (UPV), Spain, and the University of Gvle, Sweden, in 2004, and the Ph.D. degree in telecommunications from UPV in 2009. During his doctoral studies, he was a Guest Researcher at the Royal Institute of Technology, Sweden, the University of Turku, Finland, and the Technical University of Braunschweig, Germany. He also did an internship at Ericsson Eurolab, Germany. From 2010 to 2011, he was a Post-Doctoral Guest Researcher at the Fraunhofer Heinrich Hertz Institute, Germany. He is currently a Senior Researcher (Ramon y Cajal Fellow) at the Institute of Telecommunications and Multimedia Applications (iTEAM), UPV, where he leads a research group working on multimedia broadcasting, in particular on the optimization of 3GPP multimedia broadcast multicast services (MBMS) and digital video broadcasting (DVB) systems. Since 2008, he has been actively participating in the European digital television standardization forum DVB. He participated in the validation of DVB-T2, and in the standardization processes of its mobile profile T2-Lite and its handheld evolution DVB-NGH. He also contributed to the DVB-T2 implementation guidelines, and co-edited the implementation guidelines for upper layer forward error correction. He was very involved in the promotion and adoption of DVB-T2 in Colombia, and since the second half of 2012 he has been working with the spectrum regulator on the spectrum and network planning and optimization of DVB-T2. Since then, he is also a Visiting Professor at the Sergio Arboleda University of Bogota, Colombia. Dr. Gómez-Barquero is the Editor of the book, Next Generation Mobile Broadcasting (CRC Press), and the Vice-Chairman of the Modulation and Coding Ad-Hoc Group of the ATSC 3.0 standardization process.

Staffan Bergsmark was born in Stockholm, Sweden, in 1953. He received the Master of Science degree in Electrical Engineering from the Royal Institute of Technology (KTH), Stockholm, Sweden in 1981. In 1981, he joined Swedish Telecom (now TeliaSonera) where he worked with satellite telecommunication. Since 1992, he has been with Teracom. His area of work includes development of digital COFDM TV system, planning parameters for digital TV, verification of SFN networks, frequency planning of digital TV networks, mobile diversity reception of DVB-T, field measurement of system performs, coverage measurement of broadcast systems, network planning for TFS. He has participated in European R&D projects under the ACTS, IST and CELTIC programmes. He is involved in the standardization of planning parameters in CEPT and ITU.

Erik Stare received a Master of Science in Electrical Engineering in 1984 from the Royal Institute of Technology (KTH) in Stockholm. He joined Ericsson in 1984 and from 1987 Swedish Telecom (now TeliaSonera) where he was involved in R&D projects related to HDTV and digital terrestrial TV. Since 1992 he has worked at Teracom, mainly with R&D related to various aspects of digital terrestrial TV/HDTV. He has been deeply involved in the development and standardisation of the broadcast systems DVB-T, DVB-H, DVB-T2/T2-Lite and DVB-NGH and is the inventor of MPE-FEC in DVB-H and Time Frequency Slicing in DVB-T2 and DVB-NGH. He has participated in a number of European R&D projects under the ACTS, IST and CELTIC programmes.