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AN INTRODUCTION TO TIME-FREQUENCY SLICING

TECHNICAL REPORT

Geneva
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Executive Summary

This report is intended to be an accessible introduction to Time-Frequency Slicing (TFS). It pulls together the results of a number of theoretical studies and considers them in conjunction with measurements taken in the field to see how they compare. It also provides relevant background to the technique, including statistical multiplexing, and it assesses coverage scenarios which may particularly benefit from TFS.

Other aspects of TFS are also considered, such as how it might be deployed in practical networks, potential time frames for its introduction, as well as the benefits and drawbacks of the technique for consumers and broadcasters.

TFS is a DVB technique that enables multiple frequency channels to be combined into a single wider channel in order to improve the efficiency and robustness of DTT transmissions. Improvements come from two main areas:

- Frequency diversity gains. Variations between one RF channel and another in the transmission chain can be harnessed in order to improve the system's performance (e.g. differences in antenna diagrams, receiving antenna gains, interference and the transmission channel).
- Larger statistical multiplexing (stat-muxing) pools that come from a wider frequency channel.

Simulations, supported by field measurements, indicate that combining four to six RF channels may achieve, for standard fixed rooftop reception, a capacity gain of some 20 - 25%. In addition, stat-muxing gains in the order of 15% for high- and ultra-high definition (HD and UHD) programmes are expected[1]. These gains could, as is common, be used to improve the DTT proposition by introducing more services, or improving their quality. Furthermore these gains could make the delivery of UHD more practical.

Alternatively, TFS could be used to improve the coverage and/or robustness of DTT transmissions. For example, coverage deficiencies in one or more multiplexes caused by unequal interference could potentially be regained. Providing identical coverage for all the services in the TFS signal would also be possible in order to simplify the DTT proposition.

It is, however, important to understand the metric being used to calculate the TFS gain, as it may not suit all broadcasters' objectives. Canonically, TFS gain is calculated relative to the worst performing multiplex at each location. In some places, coverage will be lost from the best performing multiplex as it is sacrificed in order to improve the worst multiplex at that particular location. TFS therefore has the effect of equalising the coverage of all multiplexes in a TFS-signal and it is particularly well suited to applications where this is desirable.

In order to achieve these benefits, consumers would require new TFS-compatible receivers but they would need no further changes - their receiving aerials, for example, could remain unchanged.

Broadcasters and network operators also would only need to make comparatively few changes to their existing networks. Modulators and multiplexing systems would need upgrading and more

[1] It is unlikely that any statistical multiplexing benefits could be realised for standard definition as modern coding and multiplexing systems usually reach saturation for this picture quality.

SFN-like timing introduced, but no fundamental infrastructure changes would be necessary. For example, transmitters and antenna systems could remain in place. The main transmission-side implications would likely be to existing coding, multiplexing and signal distribution arrangements, which may need to change. More collaboration or consolidation amongst the different organisations involved in these areas may be required, and any such changes would need to be considered in the context of existing regulations and commercial arrangements.

With these benefits, TFS is an attractive option for consideration in future DTT standards where it could pragmatically be introduced alongside additional improvements such as HEVC or UHD Phase 2, making the transition to the new technology more attractive.

However, TFS also has some limitations and would place some constraints on networks in which it is deployed. These constraints could have implications for some regulatory, political and commercial aspects of DTT networks, particularly when it is necessary to maintain the concept of multiplexes or differentiate services on a coverage basis. Virtual multiplexes, through multiple Physical Layer Pipes (PLPs), may help in this regard as the essential concept of multiplexes could be retained, and services with different coverage could be delivered by using different transmission modes. Inevitably these subjects would require further consideration for the circumstances involved on a case by case basis, particularly where it is desirable, necessary, or unavoidable to deliver substantially different coverage across a number of multiplexes - wide area SFNs in particular. In these cases it may be necessary to create two or more TFS multiplexes which group together services with similar coverage.

The timescales in which TFS may yield benefits should also be considered. In order to be immediately beneficial, sufficient 'spare' spectrum would need to be available in order to combine two or more multiplexes into a TFS signal, and a sufficiently high proportion of viewers would need to have TFS capable receivers. If there is no 'spare' spectrum, the benefits of TFS may not be realised for a number of years – in the order of the lifespan of a generation of receivers.

To date no trials using TFS have been carried out, and no prototype receivers are available. The information in this document is based upon simulations and field measurements involving multiple DVB-T signals from which the performance of TFS may be inferred.

Further benefits may also be derived by combining TFS with Advanced Network Planning techniques (ANP), but these are not covered in this document.

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An introduction to Time-Frequency Slicing

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1. Background

Time-Frequency Slicing (TFS) is a DVB technique that enables multiple frequency channels to be combined into a single wider channel in order to take advantage of improved frequency diversity and wider statistical multiplexing pools. Improvement in these areas leads to efficiency gains which could be used to increase the capacity and robustness of DTT transmissions. Although it is yet to be deployed, early forms of the technique have been established for a number of years - for example the DVB-T2 specification (2009) included TFS with an informative status. The technique has since been revised and improved in further iterations of DTT standards such as DVB-NGH, where it is now possible to implement single-tuner receivers as opposed to two tuners in earlier specifications. More recently, attempts have been made to quantify the capacity gain that TFS might bring to DTT.

A number of publications, [1] [2], have set out theoretically achievable TFS capacity gains of some 20 - 25% through frequency diversity, should four or more RF channels be combined. Additional stat-muxing gains are estimated to be up to 15% for HD and UHD programmes.

Gains such as these could provide a significant boost to DTT platforms and should further be considered.

2. TFS – An Introduction

The basic premise of TFS is set out in Figure 1. Multiple frequency channels (three are shown in the figure) – which need not be adjacent[2] – can effectively be aggregated into a single, wider frequency channel.

The content of individual programmes or services is sliced up into 'blocks' of information of variable time duration. The blocks are then transmitted by systematically cycling through the frequency channels within the TFS aggregation so that consecutive blocks from each service are placed on different frequency channels.

[2] TFS may also take place over different frequency bands (e.g. Band III and Bands IV, V), provided that the same bandwidth is used in each band.

The process is set out in Figure 1 where the six different coloured and numbered blocks are associated to a distinct service.

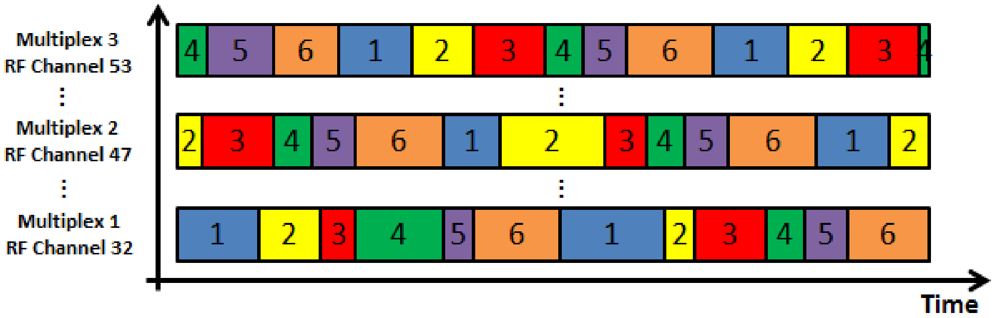

Figure 1: Overview of TFS.
A TFS aggregation over three multiplexes on non-adjacent RF Channels

The wider aggregated channel has benefits in two main areas:

- Increased frequency diversity. Variations from one frequency channel to another in antenna patterns, receiving antenna gains, and interference, for example, increase the system's frequency diversity, leading to coverage or capacity gains.
- Larger statistical multiplexing pools for variable bit rate (VBR) services.

TFS may however place an upper limit on the throughput of each of the coloured blocks above, which could affect some high-capacity applications such as UHD. § 6.7 further elaborates on this limitation.

3. Frequency Diversity Benefits

3.1 Frequency Diversity Overview

A number of areas in the transmission chain, ranging from the transmitting antenna system, to the transmission channel (including interference) and receiving system (including the receiver noise figure, receiving aerial and down-lead) will perform differently on different frequencies. For example, the antenna diagram of transmitting antennas change with frequency, the interfering and wanted signals at each receiving location often differ from one frequency channel to another, and signals naturally vary in time at differing rates on different frequency channels. The performance of the receiving antenna and the receiver itself will also vary over a range of frequencies.

Bearing the above effects in mind, transmitting services over multiple frequency channels increases the frequency diversity of the system relative to a single frequency channel. Doing this with TFS would essentially average out these variations so that the overall system's performance would, at each receiving location, be determined by the average C/(N+I) of the frequency channels comprising the signal, rather than the C/(N+I) of the worst performing multiplex, a typical definition of coverage. Viewed in this way, a TFS gain can be derived.

Figure 2, reproduced from [3], illustrates this point. The figure on the left shows that coverage varies from one radio frequency (RF) channel to another due to a combination of frequency dependant factors described above. In this case RF channel 3 has particularly good coverage compared to the other two. If, at any particular location, the overall coverage of the network is defined by the coverage of the worst performing RF channel, the red area in the right-hand figure describes the coverage; this is the area where all three RF channels provide coverage. It is referred to as the common, or core, coverage.

However, should these RF channels be combined using TFS, the core coverage could be extended by the grey area enclosed by the dotted red line. The difference between the solid and dotted red areas is shown in grey, and represents the coverage gain of TFS.

Alternatively, the capacity of the multiplexes could be increased (by changing the system variant to take advantage of the improved conditions) whilst maintaining the original core coverage. This would give a capacity gain as discussed in § 4.2.

TFS could therefore be used to realise coverage or capacity gain, or a combination of both.

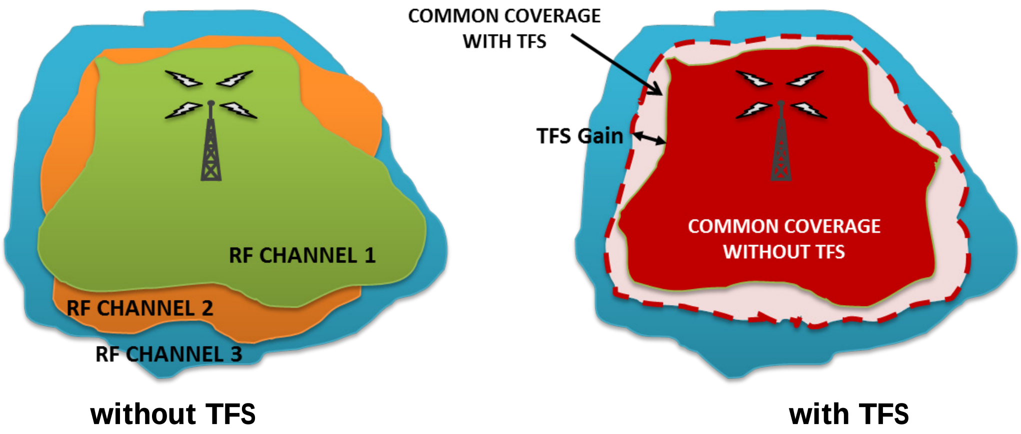

Figure 2: Example of area coverage for three RF channels in a DTT network

It is important to understand the metric being used to calculate the TFS gain, as it may not suit all broadcasters' objectives. As described above, the TFS gain is relative to the worst performing multiplex at each location. In some places coverage will be lost from the best performing multiplex as it is sacrificed in order to improve the worst multiplex at the particular location (the blue area in the right-hand figure).

TFS therefore has the effect of equalising the coverage of all multiplexes in a TFS signal and it is particularly well suited to applications where this is desirable. Indeed, coverage differences between multiplexes created by variations in, for example, interference or disparate antenna restrictions, could be overcome by this equalisation effect [4]. On the other hand, situations may arise where it is desirable to provide services with different coverage. In many instances virtual multiplexes, as set out in § 6.1, would help to provide this differentiation.

There may be some instances where the desired coverage differentiation is too great for TFS to be suitable. Careful consideration of the service objectives would therefore be necessary to determine whether TFS would indeed be a suitable technique to apply.

Other methods of assessing the TFS gain are possible and are currently being investigated. For example, a case study [5] by UPV and the IRT indicates that the TFS gain reduces remarkably if the coverage reference is taken as the average of all multiplexes instead of that of the worst multiplex. It is anticipated that consideration of this will be incorporated into an updated version of this document.

3.2 *Simulation Results*

A number of simulations have been carried out [1] [6] [7] to estimate the gain that TFS might offer for both MFNs and SFNs. The methods and results of these studies are briefly discussed below.

3.2.1 TFS in MFNs

Figure 3 sets out an ideal hexagonal MFN network with frequency re-use of N=4. Similar diagrams can be created for other re-uses, with N=7 perhaps being more typical of high power high tower broadcasting networks. Simulations of these ideal networks have been carried out for these two re-use patterns [1] in order to estimate the capacity gain of TFS compared with an equivalent non-TFS network.

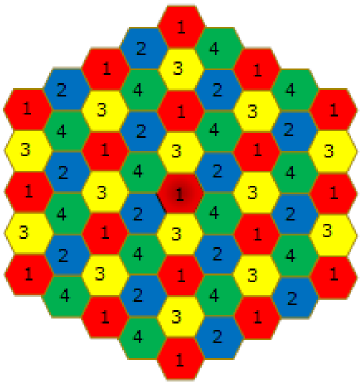

Figure 3: Ideal hexagonal network with frequency re-use N=4

The results from [1], normalised relative to non-TFS with N=7 are summarised in Table 1, where depending on the signal time correlation assumptions (C, U1 or U2) and re-use pattern, the TFS capacity gain can range from 15 - 78%. It should be noted that the presentation of the results below differs to that in the references. Below, the relative efficiencies have been derived by comparing the efficiency for TFS under particular time correlation and frequency re-use assumptions to the non-TFS case under the same assumptions. This avoids gains arising from different time correlation assumptions and re-use factors being attributed to TFS.

Table 1: Relative normalised spectral efficiency for different network configurations

	C		U1		U2	
	N=4	**N=7**	**N=4**	**N=7**	**N=4**	**N=7**
Non-TFS	1.14	1.00	1.21	1.00	1.19	1.00
TFS	1.44	1.15	1.50	1.19	2.12	1.58
TFS Gain (%)	26%	15%	24%	19%	78%	58%

Table 1 indicates that TFS would be more beneficial for lower re-use patterns than for higher patterns (i.e. N=4 vs N=7). Lower reuse patterns (e.g. N=4) generally imply that the interfering transmitters are located closer to the receiver position, which experiences a lower C/(N+I). The averaging effect by TFS allows for increasing C/(N+I) thus obtaining a higher gain. When the interference is lower (e.g. N=7) the TFS gain becomes lower since the C/(N+I) without TFS is already high, and the averaging effect has a limited impact.

The salient parameters on which the simulations were based are set out below, with further detailed information in the original paper.

- ITU-RP.1546 propagation model.

- 60 km inter-transmitter distance with 250 m effective height.
- Column C: Full time correlation: the received signals from all transmitters are assumed to be fully correlated in time.
- Column U1: All signals from each particular station are assumed to be fully time correlated. Signals from different stations vary independently in time.
- Column U2: All signals from all stations vary independently in time[3].
- Frequency selective fading (2 dB) and log-normal fading (5.5 dB) were incorporated in all calculations.
- TFS signals comprising six RF channels.

Different time correlation assumptions have been investigated since detailed knowledge about the exact correlation behaviour of broadcast transmissions is still not available; rather more qualitative assessments are usually made in broadcast predictions with regard to this aspect.

Both full time correlation (C) and no correlation (U2) may be viewed as bounding conditions. It may be reasonably assumed that signals coming from the same direction/transmitter suffer similar variations at the same moment in time. Signals from different transmitters would likely suffer different variations.

Intuitively, conditions between the two cases seem more representative of practical circumstances. Measurements summarised in § 3.4 support this view. They indicate that a TFS gain of 4.5 dB may typically be achieved with 4 multiplexes, corresponding to a 25% capacity gain for typical fixed rooftop reception.

In practice broadcasting networks often fall somewhere between reuse N=4 and N=7, which indicates that a higher TFS gains (for N=4) might also be an upper limit.

TDF assessment [6] of various metrics associated to TFS shows potential gains in capacity in the range 11 - 16% when correlated signals are assumed and at least 4 channels are used to form the TFS configuration, while gains in the range 6 - 31% might be achieved in the uncorrelated case, depending on the original difference in technical emission characteristics between the various channels. This assessment is based on the “worst C/N / worst capacity on Core and TFS location” metrics.

3.3 TFS in SFNs

Simulations of the TFS gain based on hexagonal networks representing SFNs, as set out in Figure 5, have also been carried out in [1] where the simulated network parameters (including transmitter heights, separation distances, and extent of SFN) were indicative of on-air networks in several European countries.

[3] For more information about the correlation assumptions refer to [1].

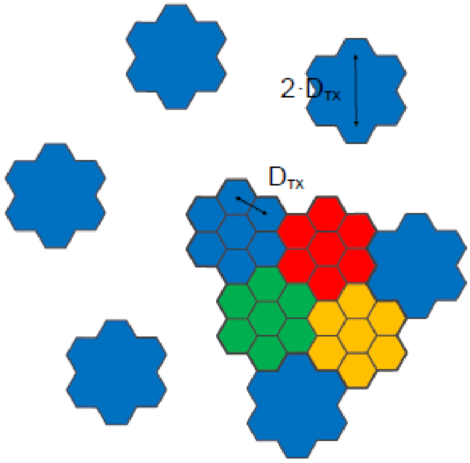

Figure 5: Hexagons representing regional SFNs (N=4)

Table 2: Relative normalised spectral efficiency for different SFN configurations

	C		U1		U2	
	N=3	**N=4**	**N=3**	**N=4**	**N=3**	**N=4**
Non-TFS	1.30	1.00	1.27	1.00	1.32	1.00
TFS	1.50	1.16	1.43	1.13	1.94	1.52
TFS Gain (%)	15%	16%	13%	13%	47%	52%

Comparing the results for MFN (Table 1) and SFN (Table 2) it can be seen that the relative TFS gain from SFNs is somewhat lower than in the MFN case. The reason is that the spectral efficiency of the SFN (which is the reference) is higher to begin with. So it becomes more difficult to increase it further when adding TFS.

The gains with MFN and SFN generally reduce with a decreasing number of RF channels involved in the TFS-Mux due to the reduced frequency diversity. Simulations with 3 and 2 RF channels indicate gains around 20% and 14%, respectively, for MFN, and 11% and 8%, respectively, for SFN [1].

3.4 TFS Measurement Results

Measurements by Teracom in Sweden, [8] [9], indicate that in practice a TFS signal comprising four frequency channels may achieve a TFS gain of around 4.5 dB over the worst performing multiplex as described earlier in Figure 2.

The measurements, predominantly taken in rural villages, also indicate that the gain would be essentially the same for fixed reception with directional antennas at 10 m above ground level (agl) and outdoor reception with omnidirectional antennas at 3 m agl.

Further measurements [7], taken in Bilbao, again over four RF channels, and in broadly similar receiving environments indicate a similar TFS gain could be expected.

These measurements can be compared to the simulations above by converting the TFS gain (in dB) to a TFS capacity gain. The following example indicates how they align.

Table 2.14 of [10] sets out the C/N of the DVB-T2 transmission mode 256 QAM 3/5 FEC PP2 GIF 1/8 (non-extended bandwidth) in a Ricean channel as 19 dB. Increasing the FEC to 3/4 would raise the system C/N to 23.2 dB, an increase approximately equal to 4.5 dB; the measured TFS gain. In these circumstances a network's capacity could be increased from 29.4 Mbit/s to 36.8 Mbit/s; a capacity gain of 25%. This is broadly in-line with the simulations.

Measurements [7] also indicate that a higher TFS gain (5.5 - 6 dB) may be expected in dense urban areas where more dominant reflections may be present.

Both [7] and [8] indicate, as expected, a TFS gain that increases with the frequency spread of the RF channels comprising the TFS signal. [3] also indicates an increasing gain with the increasing number of RF channels comprising the TFS signal, although the benefit will level off after combining four to six RF channels. In general, the achievable TFS gain is limited by the maximum separation between RF channels in the TFS-Mux.

As indicated in [3], the TFS gain as well as the field strength differences between RF channels presents a proportional relationship with frequency separation. However, increasing the number of RF channels among the two extreme frequencies do not involve large changes in the TFS gain. Note that the gain increases with the number of RF channels if the frequency separation among the extreme frequencies also increases.

Measurements also show that, for a constant number of RF channels in the TFS signal, the TFS gain increases with the channel spread – see chart below, which is based upon results in [8].

Table 3 shows an example of the achievable TFS gain when considering a TFS-Mux of 4 RF channels. The results correspond to the 6 different areas measured by Teracom. It can be seen that the most important gains are reached for the largest frequency separations between the lowest and highest frequencies in the TFS signal.

Table 3: TFS Gain for different frequency channel combinations

	f_1 (MHz)	f_2 (MHz)	f_3 (MHz)	f_4 (MHz)	$f_4 - f_1$ (MHz)	G_{TFS} (dB)
Area A	498	546	578	626	128	4.6
Area B	514	722	754	786	272	6.0
Area C	578	602	626	698	120	2.9
Area D	474	530	674	730	256	5.5
Area E	562	618	682	754	192	5.1
Area F	594	674	786	802	208	4.8

Figure 6 presents the TFS gain calculated for the different frequency combinations for Area A. As expected, gain increases with frequency separation. However, there is not the same tendency when increasing the number of RF channels for a fixed maximum frequency separation. As an example, note that the combination of f_1 - f_3 gives a gain of 2.5 dB whereas the combination of f_1 - f_2 - f_3 provides a similar gain (2.7 dB).

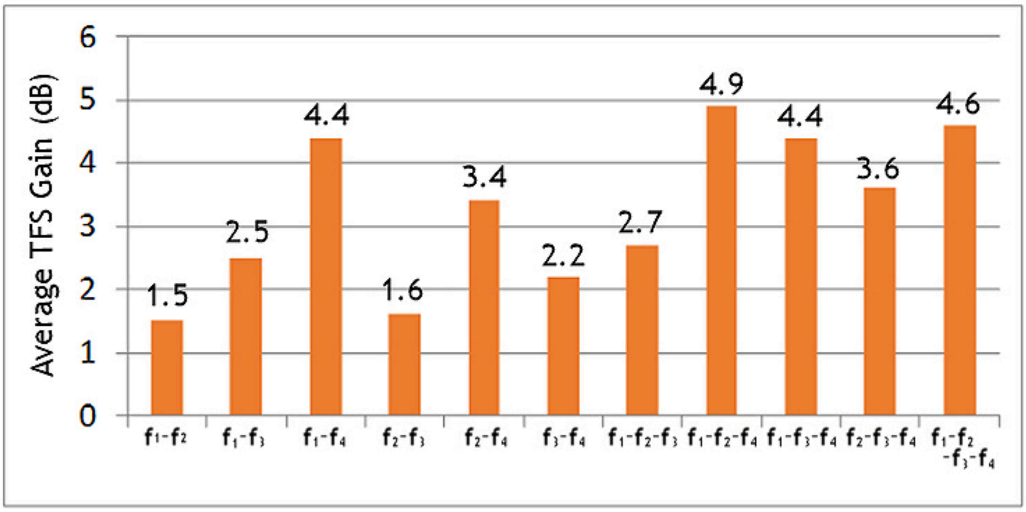

Figure 6: TFS gain for various channel spans and combinations

A similar trend is observed in [7] as summarised in Figure 7.

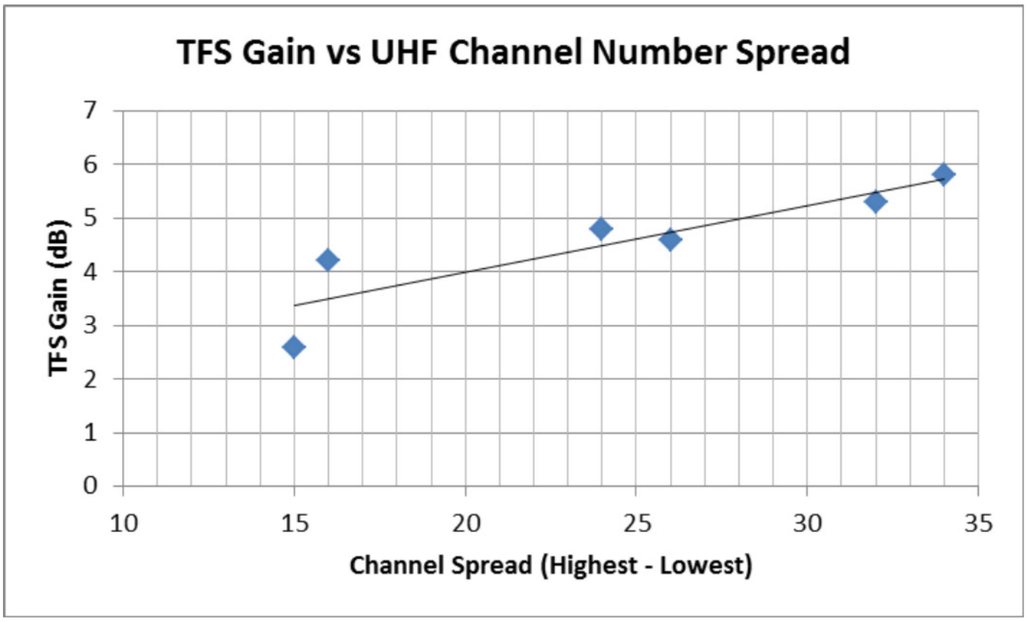

Figure 7: TFS-gain and channel spread

3.5 Mobile or Portable Reception

Mobile and portable reception will suffer from Doppler. It is seen in [7] that TFS would also offer improvements in this area with respect to the worst performing multiplex in an ensemble. For high speed reception, the worst performing RF channel is the highest frequency channel whereas, for low speed reception (pedestrian), the worst is the lowest frequency channel.

At low speeds, time interleaving becomes less effective (due mainly to finite receiver memory placing limits on the duration of the time interleaving which may be applied). Both [7] and [11] indicate TFS would provide significant performance benefits here too. Also, [11] provides an example of a TFS transmission over 4 RF channels at low speed. Time interleaving duration (100 ms – typical for DVB-T2) is not enough to cover the necessary coherence time periods to average channel variations. In such cases, TFS provides an advantage so that frequency diversity can compensate for the limited time diversity. According to the results in [11] a gain of up to 7 dB is found for the simulated scenario.

TFS is also expected to provide a higher gain in dense urban environments [7], where mobile and portable reception may be more widespread. This is attributable to greater channel variability in a multipath environment.

4. Statistical Multiplexing

4.1 Overview of Statistical Multiplexing

Statistical Multiplexing is a mature technique commonly used to increase the number of programmes that can be transmitted in a multiplex while maintaining picture quality.

It takes advantage of the fact that for a predetermined picture quality, the instantaneous overall peak bit rate of all video streams in a multiplex is significantly lower than the sum of the peak bit rates of each individual stream. By dynamically allocating each stream its instantaneously required bit rate for a predetermined picture quality, rather than providing each stream a constant bit rate can therefore allow more services to be transmitted within the same overall capacity, an outcome that leads to the statistical multiplexing gain. Figure 8 illustrates this concept.

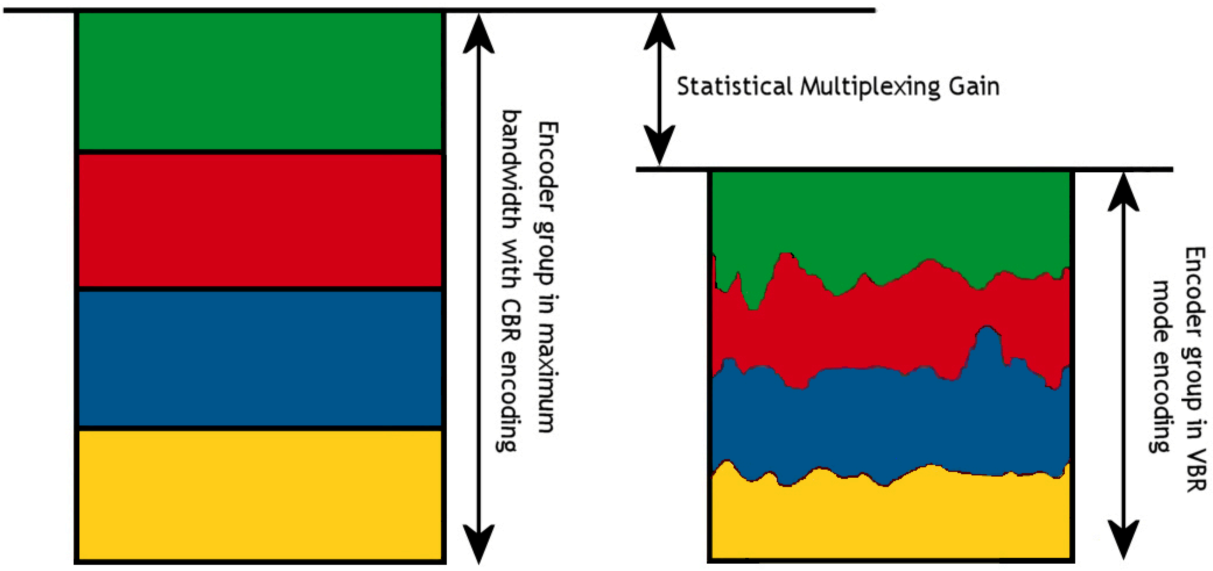

Figure 8: Overview of Statistical Multiplexing Gain

The statmux gain depends on the number of services jointly encoded and multiplexed. The gain increases asymptotically as a function of the number of services involved, until it saturates. Figure 9, from [12], sets out a typical asymptotic gain curve.

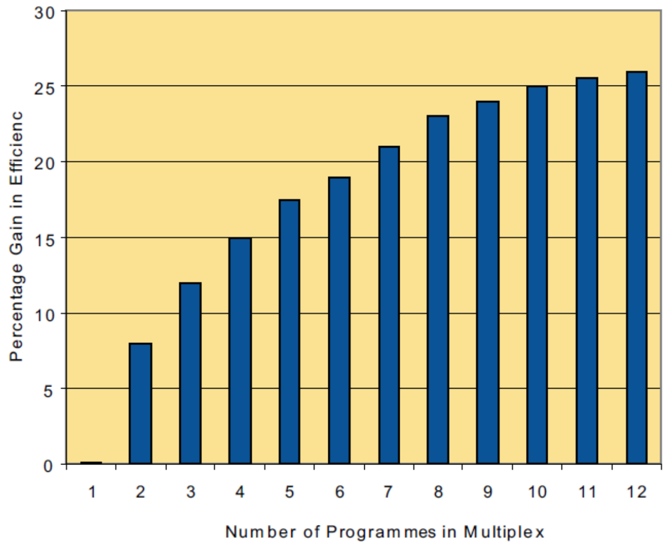

Figure 9: Efficiency gain[4] of statistical multiplexing

4.2 Statistical Multiplexing and TFS

Combining multiple frequency channels into one enables the total capacity of a multiplex to be increased. For example, combining three 8 MHz frequency channels, each capable of delivering 40 Mbit/s, would yield a single TFS multiplex with a total capacity of 120 Mbit/s (setting aside frequency diversity gains as set out previously). The higher overall capacity allows more programmes to be carried within the multiplex and the benefit of statistical multiplexing, which is a function of the number of programmes within it, to be enhanced.

Based on the methodology set out in [12], and relative to an equivalent number of independent non-TFS multiplexes, each statistically multiplexed in their own right, a wider statmux pool of TFS would broadly provide the following benefits:

Standard Definition: It is unlikely that TFS would provide any noticeable benefit as any practical DVB-T2 based network would already carry sufficient programmes in a single frequency channel to reach the saturation point of statistical multiplexing for SD programmes.

High Definition: The benefit of TFS would vary depending on the type of network deployed and the quality of the HD programme transmitted (i.e. 720p/50 to 1080p/50). Typically an effective increase in bit rate of some 5 - 15% could be achieved, generally with the greater benefit for lower capacity portable networks, and for the higher picture qualities. Furthermore, the most benefit would usually be achieved by combining a greater number of frequency channels.

Ultra High Definition (4k): assuming that the HD statistical multiplexing gains would apply to 4k, and that three 4k streams could be carried in 40 Mbit/s, effective bit rate gains in the region of 5 - 15% could be realised, again with greater benefit for lower capacity networks.

[4] Defined as: [(Bitrate without stat-muxing) – (Bitrate with stat-muxing)]/(Bitrate without stat-muxing).

5. Status of TFS – Envisaged Deployment Timescales

5.1 Status of TFS in Present and Future DTT Standards

Although TFS was incorporated in the DVB-T2 specification, it was done so with an informative or optional status. DVB-T2 compliant receivers are not, therefore, required to support it. This weaker status, combined with a number of other practical limitations such as the requirement for two tuners, has led to TFS remaining unsupported in most, if not all DVB-T2 receivers, with no known plans for its adoption.

Furthermore, due to hardware limitations, existing DVB-T2 receivers could not be upgraded to support TFS; they would require replacement. It is therefore considered most unlikely that TFS would be deployed under DVB-T2.

However, TFS has since been refined and developed to make it more practical and comprehensive. For example, DVB-NGH (ET 295 SI EN 303 105) fully supports single-tuner TFS in all profiles, including MIMO. Even so, TFS in NGH still contains some limitations which would ideally be overcome in a further update to the technique.

Traditionally, new DTT technologies have been successfully introduced using the pragmatic approach of incorporating multiple receiver improvements at a time in order to provide much enhanced services and reduce viewer disruption. For example, DVB-T2 receivers are generally made compatible with the more efficient MPEG-4 codec. In a similar way, TFS could be refined and deployed by releasing a new terrestrial DVB standard incorporating improvements in a number of areas such as: HEVC, Layer Division Multiplex (LDM), MIMO, optimised FEC codes and non-uniform constellations etc.

TFS is therefore most likely to be launched on a DTT platform through a future standard incorporating a number of improvements in many different areas.

In the current standardisation of ATSC 3.0, so called channel bonding is included [3]. This technique shares similarities with TFS in the sense that it also breaks with the tradition of transmitting a service over a single RF channel. However, as defined in ATSC 3.0, channel bonding is only performed across two different standard-bandwidth RF channels (6, 7, or 8 MHz) which could be merged to provide a total bandwidth of 12, 14 or 16 MHz. The channels can be located at any frequency, not necessarily adjacent to each other. Contrary to TFS, data is received simultaneously from the two RF channels. Thus, a receiver with two complete RF front-ends (i.e. tuner and demodulator) is required.

The most important advantages of channel bonding rely on an effective doubling of the throughput of a single multiplex and a simpler implementation not requiring significant changes in the transmission and reception chains. On the other hand, channel bonding limits frequency diversity as only two RF channels can be used in the case of ATSC 3.0. This reduces the gains provided by the C/(N+I) averaging between RF channels.

5.2 Drivers and Timescales for TFS Deployment

Introducing TFS would require audiences to upgrade their receivers, and in order to motivate the change they would need to see a benefit. In principle they could be offered more services, improved picture and sound quality and ease of use (e.g. simplified antenna positioning and adjustment to achieve stable reception). Broadcasters and network operators would also benefit in a number of areas.

In practice, the introduction of UHDTV Phase 2: 4k, 100+ Hz, high dynamic range (HDR), using HEVC video coding could be the most significant driver for TFS, provided that it is adopted in a future DTT standard. In particular for UHDTV the benefits of using statistical multiplexing in combination with TFS may be a significant enabler for UHD on DTT, as explained in section 4.

It could for example be envisaged that 4k, or HDR using HEVC, could be a point where TFS was introduced in order to take advantage of its efficiencies. For example it is anticipated that 4k Phase 2a (HDR) may be launched in 2019. It is also possible that a next generation DVB standard could be made available to align with this time frame.

Of course manufacturers would need to redesign the receiver chips. Informal discussions with receiver manufactures indicate that the complexity of the redesign would increase when implementing TFS. However this would only have to be done once, and the area of the chip would not need to increase. It is expected that any additional re-design effort could be absorbed into mass production and TFS capable receiver chips would not be significantly more costly.

6. Deploying TFS: Background, Network Implications and Practical Considerations

This section introduces the concept of virtual multiplexes and sets out how TFS may be deployed, also within existing networks.

6.1 Virtual Multiplexes and Physical Layer Pipes

The concept of a virtual multiplex may be an important tool for deploying TFS, particularly in existing networks where it is necessary or desirable to offer a number of multiplexes with different coverage or capacity. Virtual multiplexes would also help to maintain the concept of distinct multiplexes, possibly for regulatory or commercial reasons.

Generally, two or more multiplexes would be combined to form a TFS signal. By using Physical Layer Pipes (PLPs), the TFS signal could then be sub-divided into one or more “virtual multiplexes”, each being spread over all of the RF channels comprising it. In turn, each virtual multiplex could, through the PLPs, be assigned a different modulation, making the services within it more or less robust in order to fulfil any particular coverage targets that the services may have.

Each virtual multiplex could therefore group together services with common characteristics, such as the coverage that they might need to achieve. The concept of distinct multiplexes could thus be maintained in a TFS context, and alignment with existing regulatory arrangements may also be kept as virtual multiplexes could correspond with existing licences. When these aspects are not important, one may consider just a single virtual multiplex carried by the TFS signal, since there is not necessarily any technical difference between carrying one or more virtual multiplexes in a TFS signal.

An example is shown in Figure 10. In this figure, each TFS signal contains a number of RF channels, at a site (MFN) or a number of sites (SFN) that are using TFS at each site.

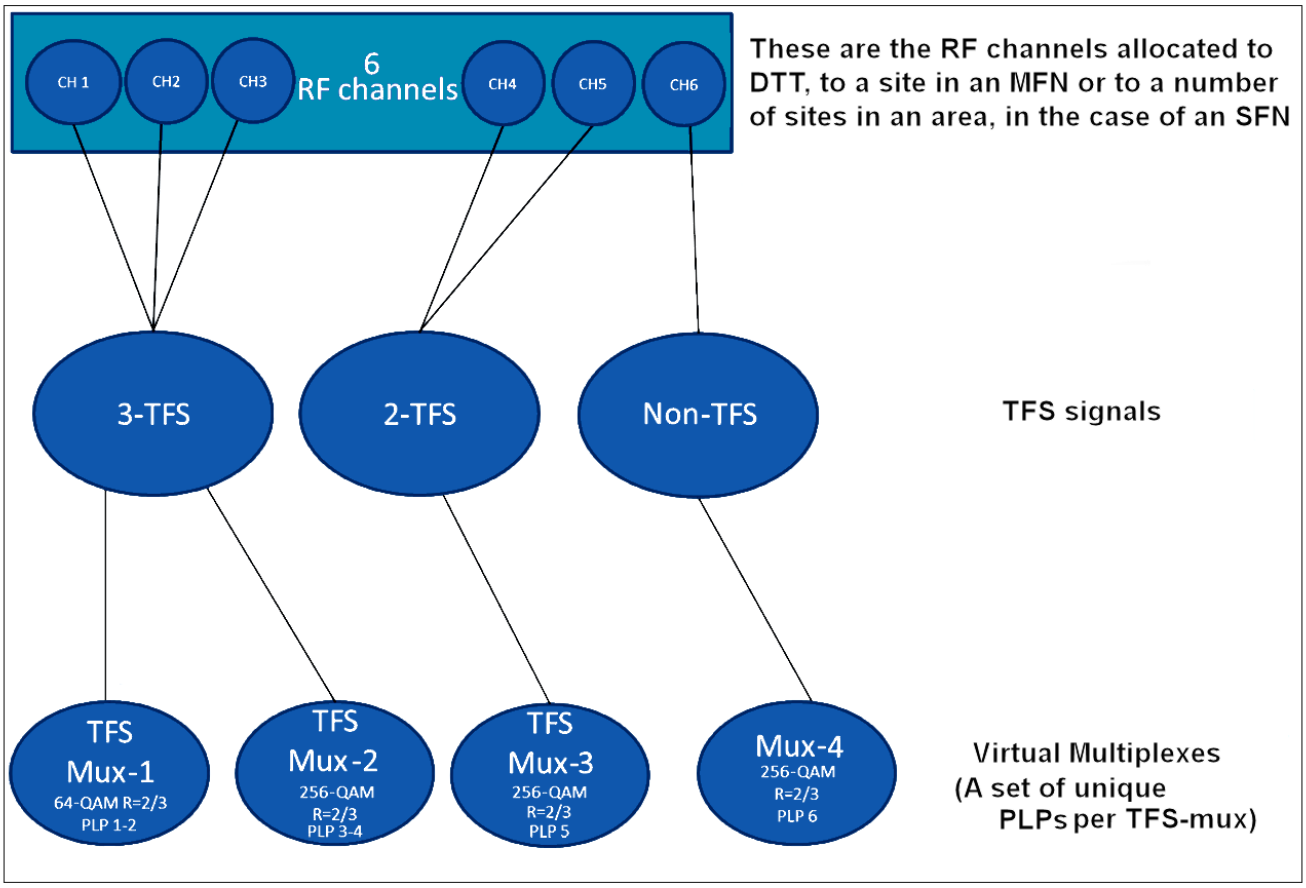

Figure 10: Example of 6 RF channels split into 3 different TFS signals

One could consider 6 RF channels forming a TFS signal that could be partitioned into multiple sub-TFS signals; four are shown in the example. One consists of 3 RF channels (3-TFS), another of 2 RF channels (2-TFS) and one is a non-TFS signal. In another scenario all RF channels could be included in a single TFS signal consisting of 6 RF channels (6-TFS). Furthermore, each of the TFS signals may be subdivided, by way of multiple PLPs, into an arbitrary number of "virtual multiplexes", sharing the available capacity, as previously explained.

6.2 Introducing TFS with a New Frequency Plan and Network Changes

A new frequency plan, unconstrained by legacy issues, would maximise the benefits of TFS. For example, simulations summarized in § 3 indicate that introducing TFS would allow a greater tolerance to interference in a tightly planned network. A network designed with TFS in mind would allow its frequency re-use factor to be reduced while improving the network's overall spectral efficiency.

Furthermore, Advanced Network Planning (ANP) techniques such as Multiple Frequency Re-use Patterns (MFRP) and Mixed Polarization Networks (MPN) could also be adopted to further enhance the benefits of TFS [1].

It is nevertheless difficult to foresee TFS based frequency re-planning, particularly with ANP, in the short to medium term as it would involve significant network and viewer disruption. It would also require a transition plan and sufficient market penetration of TFS receivers.

6.3 Introducing TFS in an Existing Network and Frequency Plan

In principle a transition to TFS in an existing DTT network (SFN or MFN) may happen without modification to the network structure and without changing the frequency plan, albeit that the full benefits of TFS may not be realized due to legacy constraints placed on the network.

Perhaps the multiplexes with similar coverage requirements and transmissions from substantially the same sites could be grouped together into TFS signals. No other substantial transmission network changes would be necessary. In such a case, the existing regional transmissions and coverage could be maintained as before; capacity gains could be realized and the coverage of many services could also be equalized, simplifying the viewer proposition.

In some cases, in order to provide services with different coverage, or to comply with regulatory and commercial constraints, it may be necessary to establish more than one TFS signal. Doing so would constrain the benefit of TFS relative to § 3, which considers more ideal situations. Virtual multiplexes may also be an effective means of resolving some of these issues.

In order to successfully introduce TFS, the disruption to viewers also needs consideration. If, as is usually necessary, it was desirable to minimize viewer disruption through loss of services, a sufficient proportion of receivers would have to be TFS compliant. Alternatively, two (or more) unused frequency channels would be necessary to introduce the new services. In many cases the latter would not be available, and without a well-publicized switchover event, the uptake of TFS receivers may take some time (in the order of the lifespan of a generation of receivers).

6.4 TFS Deployment in Practical Networks

Many practical DTT networks would suffer further constraints with respect to introducing TFS. A number of possible TFS deployment scenarios are now considered, based upon the existing DTT networks in the UK, France and Sweden. Due to spectrum availability constraints, all of these scenarios would require a transition to TFS, rather than the addition of TFS services alongside the existing services.

6.4.1 UK – Separate PSB and COM TFS Multiplexes

Three PSB multiplexes are transmitted from some 1150 transmitters, each multiplex achieving in excess of 99% population coverage. Due largely to variations in interference, the common or core PSB coverage (locations where all three PSB multiplexes are available) is lower than that of any individual multiplex, at just over 98.5%, a situation very similar to that set out in Figure 2.

The UK network also has three commercial multiplexes transmitting from around 80 sites that achieve a core population coverage of around 90%. Individually, the commercial multiplexes again cover more than this at around 91% of the population.

Setting aside viewer and legacy implications, the simplest way of introducing TFS in the UK may be to combine all three PSB multiplexes into one TFS signal and the commercial multiplexes into another. Doing so would not require the commercial multiplexes to transmit from all 1150 stations. Arranged thus, the PSB coverage areas would be made common, simplifying the viewer proposition. While the commercial multiplex coverage would remain different to that of the PSBs, all three virtual commercial multiplexes would achieve the same coverage, further simplifying the viewer proposition. The capacity available to all services would also be increased, enabling service improvements.

6.4.2 Sweden

One DTT multiplex in Sweden provides public service broadcasting (MUX 1) to 99.8% of the population from 54 main and 578 smaller transmitter sites. Another 6 DTT multiplexes (MUX 2-7) transmit from the same 54 main sites with MUX 2-6 transmitting from 106 of the smaller sites while MUX 7 uses 100 smaller sites. Coverage of MUX 2-7 is about 98% of the population. The reason for the lower number of sites used in MUX 7 is that some sites use VHF which provides better coverage. The smaller sites used in MUX 2-7 are a subset of those used for MUX 1. The DTT networks are primarily MFN, with SFNs in some areas. There are two broad options for introducing TFS in these networks:

- Apply TFS to MUX 2-6 alone. MUX 1 and MUX 7 would not use TFS since the coverage requirements are different. TFS could possibly be extended to include MUX 7 if the standard was designed to accommodate the different UHF and VHF channel bandwidths.
- TFS is applied to all multiplexes but only to common sites between MUX 1 and MUX 2-7, 54 main stations and about 100 smaller stations.

The second option would most likely mean that some of the regional SFNs would need modification and new frequencies found for the remaining sites used in MUX 1. This would probably not be so difficult since they are essentially smaller sites with limited coverage. Also the different bandwidths of UHF and VHF channels would have to be taken account of for MUX 7.

6.4.3 France

In France, 8 multiplexes provide coverage for at least 95% (effectively up to 98% on some multiplexes) of the population with various constraints and architectures:

- One multiplex is used for public service broadcasting, and has to cover at least 95% of the population nationwide and 91% of the population in any particular region. It also provides regionalized content, and is transmitted from 112 main, and more than 1500 secondary sites.
- Two multiplexes also have the 95% nationwide / 91% region wide coverage targets, without the regionalization constraint. The same sites are used as for the regional multiplex.
- Three multiplexes have a 95% nationwide / 85% region wide coverage target, without the regionalization constraint. Among these multiplexes, two use 112 main and around 1500 secondary sites. The last multiplex uses 112 sites and a restricted set of around 1200 secondary sites.
- The last two multiplexes are currently being fully deployed. The intent is to reach a 95% nationwide coverage, and use 112 main sites along with more than 1500 secondary sites.

Due to commercial and competitive constraints, the broadcasting of all 8 multiplexes for a given area may be done from a fully common infrastructure (site/antenna), partially common infrastructure (site only) or non-common infrastructure. Up to three sites corresponding to the three major infrastructure operators may be used for a given area. Furthermore, additional sites may be set up by the local authorities to overcome interference areas or to provide complementary coverage: currently more than 300 sites are deployed, providing from 1 to 8 multiplexes depending on the area.

Setting aside the way digital broadcasting is organized in France, its legal implications with regard to a possible evolution towards TFS (a multiplex operator is awarded a frequency in an area, this frequency being broadcast by a technical operator on a designated site for the area) and the existence of local authorities operated sites, a way of introducing TFS in France could be to combine at least 6 of the 7 multiplexes that don't have regional content. This combining would have to comply with the commercial/competitive constraints indicated above, as well with the rather differing radiation patterns in the coordinated areas. This could result in a homogenized coverage for those combined multiplexes, but at the expense of the targeted nationwide/region wide coverage in some areas[5], which would cause legal difficulties concerning the minimum thresholds imposed to some networks.

6.5 Transition to TFS

The deployment scenarios above describe how TFS may eventually be deployed in practical networks, and they assume a switchover rather than a phased transition. Most likely, TFS would however be introduced in a step-by-step manner rather than by an abrupt change similar to that of digital switchover.

As explained previously, the introduction of TFS would, for example, best be combined with the introduction of UHD Phase 2 and a Next Generation Terrestrial standard (NGT), which would in any case require the replacement of existing receivers. Provided that TFS was mandated in the new standard it would mean that any new NGT receiver would also support TFS. So in this respect the introduction of TFS is very similar to any change of standard.

In order to avoid disrupting the existing DTT services it would most likely mean that the new standard would need to be introduced to the multiplexes step-by-step. Upgrading the receivers would need to be beneficial for the viewers and give access to new enhanced services. As soon as two multiplexes are broadcast with the new standard, and the penetration of TFS receivers is high enough, these could be combined into a TFS signal. As further multiplexes are migrated these could also be included in the TFS signal, or a separate new TFS signal could be created. Once receiver penetration reaches a certain level all multiplexes could be migrated. There is, as always, a needed balance between maintaining the old services and adding the new, and the actual approach would be different in each country. Here of course the limited spectrum availability for DTT will have a large impact, and unless 'spare' spectrum is available, it is likely that the benefits of TFS would take some time to realize.

Most likely TFS will initially be introduced into an existing frequency plan. This means that TFS would be used for increasing transmission capacity, by using a less robust mode (with higher bit rate) compared to the non-TFS case. Alternatively TFS could be used to equalize coverage and improve robustness to interference and time variations in quality.

6.6 Viewer Implications

As set out in § 5, in order to benefit from TFS, all viewers would require a new receiver. But, it would be pragmatic for TFS to be deployed with receiver improvements in other areas such as HEVC. In this way TFS receivers could be deployed gradually, with the deployment of TFS services occurring when sufficient receivers were in the market.

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[5] Teracom's results show a log-normal distribution of TFS gain, which suggests that the resulting averaged coverage will still be led by the worst case coverage, even if this worst case coverage benefits from 4 - 5 dB TFS gain. A detailed analysis would help decide, on a case by case basis whether it is better to 'fill in' coverage holes due to restrictions, or maintain capacity.

Importantly, TFS on its own (i.e. without ANP, MIMO etc.) would not require viewers to replace or upgrade their receiving aerials as it would be compatible with their existing installations; an attractive outcome for both viewers and broadcasters.

Additional benefits for viewers would be improved quality, for example UHD, and a greater range of programmes.

A combination of the following benefits could be made available as desired:

- More reliable coverage (e.g. with respect to tropospheric interference and time variability in portable reception environments).
- Consistent coverage over several multiplexes (potentially all).
- Easier optimization of antenna position (single figure of merit to maximise).

6.7 Network Implications

All of the multiplexes aggregated into a TFS signal would need to be time-synchronised so that receivers could hop from one frequency to another between sub-slices. This could be achieved in the same way that SFN are synchronised, by GPS, for example. As SFN-static timing delays are generally much shorter than the TFS switching time, TFS synchronising requirements are not expected to affect SFN operation (and vice versa) should the two be combined.

Single-tuner TFS places a limit on the peak data rate for an individual service, which is linked to the number of channels included in the TFS configuration[6]. For example for a single channel capacity of 40 Mbit/s and 3 RF channels using a TFS configuration, the peak data rate of an individual service is limited to 28 Mbit/s, while for a 6 RF channels TFS configuration, the peak data rate is limited to 20 Mbit/s. These limits need to be borne in mind when establishing a TFS service, and in particular when converting existing conventional multiplexes to TFS, but they would not be problematic if the peak data rate of isolated services falls below the threshold. Very high quality UHD services would, most likely, require the most careful consideration in this regard.

A common multiplexing and distribution arrangement would be necessary in order to ‘slice’ and schedule individual services across all the multiplexes comprising the TFS signal. This would most likely entail a common multiplexing facility where the operation from playout to distribution to the transmitters was to be combined into one system.

Common transmission sites would also be preferable for all multiplexes within the TFS signal, although it would be possible to use different masts for different RF channels as long as the target coverage area was substantially the same, if for example this is the existing situation with non-TFS. In this case common synchronisation between the masts would need to be used, for example using GPS.

Such a consolidated arrangement, if it did not already exist, could be associated with significant benefits introduced through economies of scale and consolidation whereby broadcasters could share costs, rather than operating their own independent systems in which equipment, functionality and costs are duplicated.

Such consolidation, and the potential collaboration required between organisations within the

[6] TFS implemented with multiple tuners would not suffer from the limitation above, although it would increase receiver costs.

transmission chain (network operators, coding and multiplexing facilities and infrastructure providers etc.) may require careful consideration with respect to regulatory, economic and legal frameworks. These aspects would require further study on a case by case basis where each may be of greater or less significance depending on the particular circumstances. Additionally broadcasters' abilities to provide significantly different coverage from one multiplex to another would be somewhat constrained, as set out in § 3 and § 6, which would also need careful thought.

6.8 Summary of TFS Deployment Aspects

Very clearly, the benefits of TFS would be maximised if it were introduced into a network specifically designed with TFS in mind and potentially including ANP techniques. However, it is more likely that it would be deployed within existing networks where it would be subject to legacy constraints and requirements. For example, regulatory and commercial reasons may make it necessary to maintain the concept of traditional DTT multiplexes, or it may be necessary to closely match the existing coverage on a multiplex by multiplex basis.

Multiple PLPs would enable virtual multiplexes. These would maintain the concept of traditional multiplexes and they would enable different services to have different coverage by applying different modulation and coding schemes to particular services through PLPs. In this way many legacy constraints may be met or overcome.

Case studies from three different countries indicate that TFS could, from a very simplistic point of view, be deployed in practical on-air networks in relatively straightforward ways. One country, the UK, for example, could adopt two TFS multiplexes, each grouping services with similar coverage. One TFS multiplex could be used for three PSB multiplexes, and another for three commercial multiplexes. Additional commercial and regulatory aspects would also need to be considered in this context.

The main impediment to adopting TFS might be where very different coverages need to be combined. In these cases it may only be possible to deploy TFS across two or three multiplexes which have substantially similar coverage. Even so, TFS would have some benefits in these cases.

The transition to TFS requires some thought. As two or more frequencies are required for a TFS multiplex it may be difficult to find enough 'spare' spectrum to introduce TFS without causing viewer disruption. With such spectrum constraints, it may take some time (the time required for a generation of receivers to work their way through the market) before the benefits of TFS could be realised.

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