



# **Study Mission Reports: Commercial & Technical Reviews of WiB**

**CM-WiB Study Mission**

**TM-WiB Study Mission**

**June 2018**

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This DVB publication makes the final reports of Commercial and Technical Study Missions into Wideband Re-Use 1 (WiB) publicly available.

While the reports are published in full, it should be noted that their conclusions and recommendations were intended for DVB's Steering Board. The Steering Board decided, in July 2018, that WiB did not constitute sufficient reason to start developing a new DVB terrestrial system at that time.

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*Note: the page and section numbering of the two original documents has been preserved.*



# **Commercial Review of WiB**

## **CM-WiB Study Mission Report**

**June 2018**

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## Executive summary

WiB is a candidate technology for next generation Digital Terrestrial Television (DTT) systems. To understand in more detail the implications of WiB for terrestrial broadcasters, DVB created two study missions:

- Within the Commercial Module, CM-WiB has studied commercial aspects of introducing WiB;
- Within the Technical Module, TM-WiB has studied the technical capabilities of WiB.

This report is the result of the work done in the CM-WiB Study Mission Group.

In DVB, interest in WiB was triggered by a paper<sup>1</sup> presented by Erik Stare from Teracom, and others, at IBC in 2016. This paper outlined the basic principles of WiB, which are the use of wideband RF channels, frequency re-use 1, the use of Layer Division Multiplexing and Interference Cancellation. It also set out potential capacity gains and ideas for migration from conventional networks to WiB as well as potential capex and opex savings. These ideas are explained in more detail in section 1 of this report.

CM-WiB has built upon SB2333, “A Long Term Vision for Terrestrial Broadcast”, a Study Mission report of CM-T. It has also analysed a Radio Spectrum Policy Group report for broadcaster technology trends in Europe and interviewed a small number of broadcast organisations for their views about the future of DTT.

CM-WiB has explored various potential business cases for WiB. Usually the introduction of a new physical layer requires new receiving equipment, which in turn requires the introduction of attractive new services to encourage consumers to buy it. UHD is the most obvious prospect, but the group has found only a very limited number of organisations with firm intentions to introduce UHD on DTT; there were more who have a firm plan not to introduce UHD. Those who have plans for introduction of UHD believe that DVB-T2, combined with new video coding techniques, would be adequate for their needs. We similarly did not find strong support for other services that might take advantage of the higher capacity that a WiB network could offer.

The Study Mission Group noted that there are various ways that existing platforms can increase their capacity at a more modest cost and with less upheaval compared to introducing WiB, including making their existing networks more efficient, and expanding services over IP. With many organisations having recently carried out major engineering works on their DTT networks for digital switchover and 800 MHz and 700 MHz clearance, there is little appetite to undertake further major network changes. There are also serious implications for important applications which are authorised to share UHF spectrum.

## Conclusions

The CM-WiB Study Mission has completed its work and concluded that there is insufficient market interest in WiB for it to be taken further at this time.

In summary:

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1 WiB – A New System Concept For Digital Terrestrial Television (DTT), E. Stare, J.J. Giménez, P. Klenner

- 1) A pan-European introduction of WiB would be needed to realise the full potential of the technology and to prevent cross-border disturbances between networks. However, large scale coordination might not be feasible in reality;
- 2) There is insufficient commercial demand for applications/services to justify transitions to WiB-based networks;
- 3) Applications such as PMSE that currently share UHF spectrum with DTT could be adversely affected;
- 4) A change from DVB-T to DVB-T2 and/or from MPEG-2/MPEG-4 video coding to HEVC or VVC would lead to significant gains in terms of service quality and/or number of services that could be provided;
- 5) There is a mid- to long-term perspective for Internet-based distribution of TV services (see e.g. DVB-I/Low Latency DASH/ABR Multicast) complementing DTT and other conventional means of TV distribution to the audience.

Interested DVB members should continue to monitor developments in advanced modulation systems and bring them to the attention of either DVB-CM or DVB-SB if there are good grounds to believe that they may change the market view.

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## 1. Description of WiB

### 1.1. What is WiB?

WiB is a candidate technology for the next generation of DVB digital terrestrial networks. The name stands for Wideband Re-Use 1. This section explains what this means, and some of the opportunities that WiB brings for the introduction of additional technologies.

### 1.2. WiB core technologies

#### 1.2.1. Frequency re-use

Digital Terrestrial Television (DTT) is carried throughout the world mainly<sup>2</sup> on UHF channels, in Europe numbering from channel 21 upwards. At present, in many locations channels up to and including channel 60 are still available, but with the transfer of the 700 MHz band to mobile communications, DTT networks will, in due course, be restricted to channels 21 to 48 in UHF.

In a conventional DTT network, i.e. a multi-frequency network (MFN), typically several high-power transmitters are used to serve a given area, each carrying a multiplex of up to about 40 Mbit/s in a single 8 MHz wide channel (other channel bandwidths are used, e.g. 6 MHz). Usually the area served by one transmitter is much smaller than the size of the country it is in, so a number of areas must be established, each with its own transmitters, in order to cover the whole country.

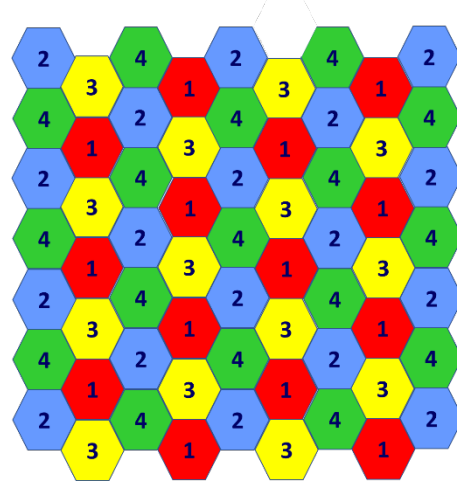
The nature of the signals we currently use in these networks makes them quite sensitive to interference from other transmitters using the same RF channels, meaning that a channel in use in one area cannot be re-used in an immediately neighbouring area. It turns out that, to cover large regions, usually 5-6 RF channels are needed for each multiplex that is transmitted<sup>3</sup>. This is termed the re-use factor and describes the amount of spectrum in the form of UHF RF channels that is required to provide a single multiplex of programme content to a region which is divided into a number of service areas. This frequency re-use factor explains why it is only possible to have about six or seven multiplexes in each service area, even though there are 28 UHF RF channels available.

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2 VHF band III is also used.

3 There is an alternative approach to this in the form of large area Single Frequency Networks (SFNs), which allow the use of the same RF channel in neighbouring service areas provided that all the services carried are identical. This constraint prevents the provision of regional content in just a partial area of the entire SFN area.

Frequency re-use is illustrated in Figure 1. Each hexagon represents an idealised service area with a conventional DTT transmitter at its centre. Each colour represents a UHF RF channel that is being used, and it can be seen that no two adjacent areas have the same colour. Further, a colour is not re-used closer than the width of a hexagon from another area that uses it. This minimum distance ensures that the level of interference from one area into another that uses the same RF channel will be sufficiently low as not to significantly impair the quality of reception.



*Figure 1 Hexagonal frequency service areas*

This arrangement illustrated in Figure 1 has four different colours, indicating that a network built on these lines would be described as re-use 4, and it could provide seven multiplexes in each area, given the availability of 28 RF channels. As noted above, real networks normally have re-use factors between 5 and 6.

The new idea with WiB is to make each transmission much more robust to interference, to the extent that the same RF channel can be used in the adjacent service area. This arrangement is called re-use 1. However, to make the signal sufficiently robust, we pay a penalty: the capacity of a single RF channel drops significantly. In a WiB network, we compensate for this reduction in capacity by increasing the number of RF channels that we transmit on - hence the term Wideband in the name. In a re-use 1 system, in principle all 28 RF channels are available in every service area.

Using all the available RF channels takes the capacity of the WiB network back up to roughly the same as a conventional network, so at first glance, we do not appear to have gained anything. However, when using WiB, the power level required for covering a specific geographical area with a certain data rate is around one tenth of the power required for covering the same area with the same data rate based on the conventional transmission approach. If WiB is used for the entire network, this can bring about both capex and opex savings at transmitters: it should be possible to transmit on all the RF channels using just one amplifier, which also eliminates the need for costly high power combining equipment; transmitter cooling systems are much smaller, and electrical power consumption is greatly reduced.

It is likely that WiB, even in a basic form, will allow an increase in spectral efficiency of around 30% to 60% compared to a conventionally planned, T2-based MFN. So, in addition to the power saving mentioned, a higher overall capacity would be achieved for the network.

However, it should be noted that the potential for WiB will differ from country to country. For example, in Italy the re-use factor for the DVB-T2 network after switch-over from DVB-T in 2022 will be about 2. This can be achieved due to the screening effect of the Alps and the surrounding Mediterranean Sea. Nationwide SFNs will be used on 70% of channels, and region-wide SFNs for 30% of channels. Subsequent introduction of WiB and re-use 1 would cause a loss of spectral efficiency estimated at 30% to 50%.



Another factor influencing the potential gains of WiB is the commercial or regulatory need for regional services over national services. Subject to further study it is anticipated that national networks would be more efficient than the regional WiB scenario, as is the case for conventional networks.

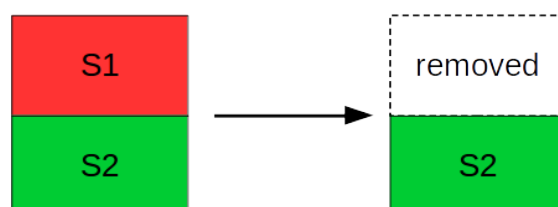
As well as the core features of WiB that can provide advantages over conventional networks, the next section describes some of the other possibilities that are enabled by using WiB.

### 1.2.2. Spectrum sharing and interference cancellation

We have already seen that re-use 1 makes WiB signals highly immune to interference coming from transmitters using the same RF channel (co-channel) in neighbouring service areas. It follows that a WiB signal will be similarly immune to co-channel signals coming from the same transmitter as the wanted signal. Furthermore, there is a way of recovering the co-channel signal, known as interference cancellation, allowing the spectrum to be used more than once in the same location.

Imagine a WiB signal S1 being transmitted from a site where the same antenna is used to transmit another signal S2 at lower power than S1, and on the same frequencies. Provided the power of the S2 signal is received more than a certain minimum value below the power of S1, it is possible to decode S1 effectively free from errors. The receiver can then re-construct the S1 signal and subtract it from the signal coming from the receiving antenna, leaving just S2, which can then be decoded.

This transmission format is known as Layer Division Multiplexing, LDM, where S1 is in one layer, and S2 is in another layer. In principle, it is possible to have more than two layers.



*Figure 2 Interference cancellation allows separation of the layers*

There are several constraints which must be met, including:

- Wherever S2 is transmitted, S1 must be transmitted from the same antenna so that their relative powers are maintained across the whole service area. (There may be sites where only S1 is transmitted.)
- In this example, a receiver requiring to demodulate S2 must also be able to demodulate and remove S1.

S1 and S2 in this example could both be broadcast signals, but do not have to be. For example, one or more could be unicast broadband data.

### 1.2.3. Improvements with new antennas

Although it is commercially highly desirable to keep legacy receiving antennas it is worth noting that when new receiving antennas are considered, much higher spectral efficiencies may be feasible,

although studies and results are only preliminary at this stage. There are mainly two different options for this, which may even be combined:

In a first variant the receiving antenna is basically as it is today but with one or two small “helper” antennas added, which are only used for interference cancellation. The idea is that in a worst-case reception situation, with one wanted signal and with interference received from two different adjacent transmitters (or SFN clusters) the use of three receiving antennas would allow the required interference cancellation, i.e. the two unwanted signals could thereby be cancelled via the appropriate receiver processing. If this is successful, performance is principally limited by noise and interference from far-away transmitters (or SFN clusters), the level of which can be made very low using the appropriate network design, e.g. using large SFN clusters and sharp vertical transmitter antenna diagrams with a degree of vertical down-tilt.

To avoid the need to replace downloads in this variant, the helper signals could be transposed at the antenna, in something resembling a mast-head amplifier, so that all three signals can be delivered to the receiver via a single download. The receiver would then need to have either three tuners, or perhaps one single wideband tuner/demodulator system.

With the adjacent interference cancelled and with the far-away interference being low, the prerequisites then exist for achieving very high spectral efficiency. Although technical studies are preliminary, and further work is required to get conclusive results, the results so far suggest that the achievable spectral efficiency may be increased very significantly (maybe by a factor of around 3-4) compared to what could be achieved with legacy antennas and conventional planning. It seems technically possible to design a WiB system in such a way that a very significant portion of the users (who have good enough reception conditions) could receive such transmissions with their legacy antenna, but they would of course need a new receiver.

In a second variant, independent of the first one, both polarisations are instead explored using cross-polar MIMO. A new MIMO antenna could simultaneously receive independent signals on the two polarisations, so capacity could be significantly increased compared to WiB using a single polarisation. Currently most broadcast transmissions use horizontal polarisation (at least from high towers) and receiving antennas are adapted to this. Incoming signals using the opposite (vertical) polarisation are very significantly attenuated by the characteristics of the receiving antenna. This is however not enough to allow simultaneous horizontally and vertically polarised signals using today’s DVB-T2 broadcast parameters but is likely to be feasible with a more robust WiB system (employing e.g. QPSK). Such a scheme would thereby allow backwards-compatibility in such a way that a basic WiB signal could be received by users with legacy antennas. These users could not receive the services on the vertically polarised signal but would not be disturbed by that signal either. Users with a new cross-polar antenna could receive the full set of services using both polarisations.

Finally, it is also possible to combine the two above approaches so that the antenna-based interference cancellation method, could also be used together with the cross-polar scheme, which would allow higher bit rates per polarisation. This could allow an even higher gain than any of the two described methods separately.

### 1.3. International coordination

National WiB networks can effectively only be deployed if WiB networks are also adopted in all relevant neighbouring countries. This is necessary for preventing cross-border harmful interference caused by a newly introduced WiB network in country A that would affect an existing conventional network in neighbouring country B and vice versa. For successful deployment of WiB, neighbouring networks must also be technically aligned and synchronized. In border areas the operational performance of networks in one country would thus be linked to the performance in its neighbours, particularly with respect to synchronisation. This is a new consideration that goes beyond conventional frequency coordination.

### 1.4. Further technology considerations if WiB is introduced

#### 1.4.1. Statistical multiplexing

Statistical multiplexing is a long-established technique for allowing a group of video channels to co-operate with each other over the use of a fixed amount of capacity. Video encoders tend to produce higher volumes of data when there are a lot of detail, motion and scene changes. This extra demand for capacity from an encoder is normally short-lived and can be satisfied by briefly providing a small amount of capacity from each of the other encoders in the same statistical multiplexing group. The outcome is higher and more consistent quality of pictures, but the process is reliant on there being an adequate number of video channels in the group.

The graph<sup>4</sup> shows that the gain of a statistical multiplexing group increases with the number of video channels. In a conventional DTT system, quite large numbers of standard definition channels can be combined in a statistical multiplexing group in a single DVB-T2 multiplex, giving a high level of gain. With high definition, the number of video channels that can fit into a single multiplex is reduced, but the gain is still significant. However, with UHD, only 1-2 channels could be carried in an 8 MHz channel using DVB-T2 (assuming physical layer net throughput of 40 Mbit/s), due to UHD's high bit rate. Additional statistical multiplexing gain could be achieved if it is possible to increase the capacity of the multiplex carrying it.

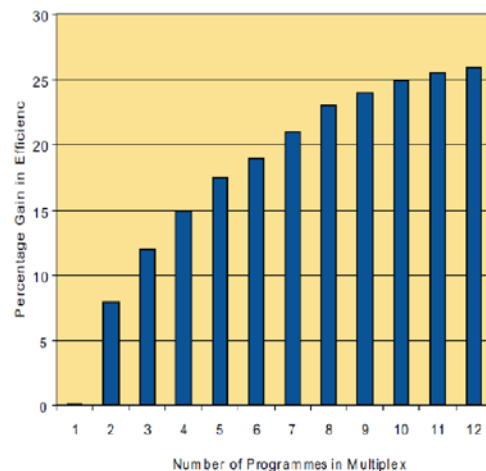


Figure 3 Indicative statistical multiplexing gain for MPEG2/4 encoded SD and HD programmes

Changing a conventional network to a WiB network brings the opportunity to aggregate the capacity of individual RF channels, effectively making multiplexes of much higher capacity. In principle, the whole UHF band could be used to make one high capacity multiplex, known as a supermux, of over 200 Mbit/s. This would enable the highest possible multiplex gain, even for UHD services. However, this would have commercial and licensing implications which need to be overcome before any

<sup>4</sup> EBU Technical Report 015. Defining Spectrum Requirements of Broadcasting in the UHF Band.

implementation could take place. On the other hand, a WiB-based DVB-T2 multiplex of, say, only 24 MHz bandwidth would see a negative statistical multiplexing gain.

#### **1.4.2. Cross polar MIMO**

Transmitting WiB signals using both polarizations – i.e. applying MIMO – might lead to further spectral efficiency gains. In the absence of related simulation results up to now, concrete figures can't be provided yet.

Use of the opposite polarisation would not be compatible with existing receiving antennas, so replacement antennas would need to be installed to take advantage of this feature. However, services could be divided between e.g. horizontal and vertical polarisations so that an acceptable set of channels is available on the existing polarisation, with access to additional services in the opposite polarisation being presented as an enhancement that comes with a replacement antenna. Another option is the application of scalable video coding to the two parallel signals on air, i.e. on the polarization compatible with existing rooftop antennas the base layer of the video stream would be provided, on the other polarization the enhancement layer data would be available for those who are investing in new antenna equipment.

#### **1.4.3. Time Frequency Slicing (TFS)**

Due to its wideband nature WiB lends itself well to be used together with Time Frequency Slicing (TFS), which may allow close-to-ideal statmuxing also of UHD services, consistent coverage across potentially all transmitted services (or selected subset thereof) and generally increased robustness against various sorts of interference, which improves network performance and facilitates co-existence with other systems (e.g. existing DVB-T/T2 or mobile telecom systems).

### **1.5. Other technology advances that might be combined with WiB**

#### **1.5.1. Latest generation video coding**

Rather like Moore's Law for semiconductors, each new generation of video coding enables the same picture quality to be achieved at roughly half the bit rate of the previous generation. Changing the physical layer of a broadcast system presents an opportunity to change the A/V coding at the same time. However, modern TV receivers are designed for global markets and receive content from many sources. So, when presented with such an opportunity, the broadcast system needs to consider the A/V decoder trends across a wide range of media and geographies. With all that in mind, if a broadcaster decided to consider WiB, it could also consider adopting the latest A/V coding solution as part of the service implementation.

## **2. Commercial drivers – based on a full WiB implementation**

### **2.1. Use cases for WiB**

Several use cases have been identified where WiB may either provide improvements over existing systems or establish new opportunities. These are:

- Improving existing DTT services e.g. more, or better-quality SD and HD TV content
- Introducing new UHD services on DTT
- Delivering DTT services more cost effectively

- Spectrum Sharing
- Filecasting
- Rural broadband

Each of these cases is discussed in more detail below to determine whether there may be any demand for WiB in any of these areas or whether it may provide some form of benefit.

#### **2.1.1. Improving existing services**

The main way in which WiB may improve existing linear DTT services is by providing greater capacity that could be used to deliver more, or better-quality SD and HD programmes.

The CM-WiB study mission found no direct demand for WiB as a means of increasing capacity that would allow more SD or HD programmes to be carried on the platform, see broadcaster interviews, section 2.2. Broadcasters pointed out that they were planning to develop their platforms based on existing technologies, with some organisations intending to add more multiplexes. Furthermore, some broadcasters highlighted that they are also focussing on IP delivery. HbbTV, for example, could supplement DTT by adding further capacity, personalised services and catch-up TV.

The responses to the RSPG questionnaire, see section 2.3 indirectly support these findings. They show that most European countries (26 out of 31 respondents) continue to operate multiplexes using DVB-T in combination with MPEG-2 or MPEG-4. Only two countries have converted, or plan to convert, to DVB-T2/HEVC. Demand for additional SD or HD capacity may therefore be more conveniently met by the continued migration to more efficient transmission and encoding standards that are already widely established today. Although this approach would require new receivers for some consumers (i.e. in cases where a physical layer or encoder standards were changed), compared with a migration to WiB, the impact would be lower for viewers, and the transition much more manageable for broadcasters.

Countries that have only recently deployed DVB-T2 HEVC are unlikely to initiate the further refresh cycle that WiB would entail until their existing amortisation period has lapsed, for example in the order of ten to fifteen years' time.

In Europe the demand for WiB in this context appears to be weak, particularly for the foreseeable future. The further deployment of more efficient, existing transmission standards appears to be more attractive for broadcasters, particularly when supplemented by IP based delivery systems such as HbbTV.

#### **2.1.2. Delivering DTT services more cost effectively**

Although the extent of any savings that WiB might offer are yet to be quantified, and would depend on the circumstances at hand, WiB has the potential to deliver services more cost effectively than DTT systems in use today. Savings could come from lower power costs (due to lower power transmissions) and other lower opex costs from simplified network design and simpler, more standardised equipment across the network. For example, wide band amplifiers could avoid the need for combiners (however output filtering would still be required), see Annex A for more information.

Cost savings would however only be realised following the installation of a substantially new network, see Annex A. The new network would itself incur costs.

Although an attractive feature, the power saving aspect of WiB is not therefore considered a sufficient justification on its own.

It is also expected that any operational cost savings that WiB may make possible would only outweigh the cost of a new network – and this is subject to confirmation – should it be possible to align equipment upgrades (to WiB-capable equipment) with the planned refresh cycles of existing networks' constituent parts. Managing upgrades in this way would avoid the costs of writing down existing assets that would otherwise be necessary. However, the complex nature of a WiB transition would make it unlikely that such alignment could be realised. All relevant neighbouring countries, see section 1.3, would have to agree in advance to a synchronised transition before any individual country could itself begin to install WiB-compatible equipment, in anticipation of using it in the future. Such a situation appears unlikely, making WiB's potential opex cost savings correspondingly uncertain.

The potential cost savings of WiB are not therefore considered to be a clearly defined source of demand.

### **2.1.3. Introducing new UHD services**

At the time of writing UHD content is becoming more widely available with regular services emerging on satellite, cable and IP platforms, often aimed at the premium end of the market<sup>5</sup>. Additionally, UHD display panels in new TVs are becoming widespread, with figures from the UK revealing that 72%<sup>6</sup> of all panel sales are UHD ready.

Despite these developments, no UHD services, either ad-hoc (i.e. key events) or permanent, are known to exist on any DTT platform. Capacity constraints may, at least partly, explain this absence. For example, today a DVB-T2 HEVC multiplex would be able to carry only 1 to 2 UHD programmes; a proposition that is so far insufficiently attractive.

WiB's higher capacity and wider bandwidths, including better properties for statistical multiplexing, see section 1.4.1, may therefore be attractive for delivering UHD.

However, plans for carrying UHD on DTT platforms are currently few, see sections 2.2 and 2.3, with more organisations planning not to introduce UHD on their terrestrial networks, and those planning for UHD believe that DVB-T2, combined with new video coding techniques, would be adequate for their needs. Some of the broadcasters interviewed referred to their experience with HD, pointing out that audience uptake of HD was relatively low, and that advertising revenue is the same for SD and HD. They foresee a similar situation for UHD, expecting it to be limited to premium content, home cinema and similar applications, rather than for general TV services.

No strong demand was found for WiB in relation to UHD.

### **2.1.4. Spectrum sharing**

WiB offers the potential for sharing spectrum between broadcast and other services such as mobile, see section 1.2.2. One organisation we interviewed sees spectrum sharing as a means of ensuring

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<sup>5</sup> [https://www.ofcom.org.uk/\\_\\_data/assets/pdf\\_file/0022/108517/connected-nations-evolution-television-2017.pdf](https://www.ofcom.org.uk/__data/assets/pdf_file/0022/108517/connected-nations-evolution-television-2017.pdf)

<sup>6</sup> Derived inter-alia from GfK sales data

broadcasters' continued access to spectrum that would otherwise be re-allocated to mobile. In contrast, Ofcom, the UK regulator, has recently published<sup>7</sup> its belief that demand for the 600 MHz band to be re-allocated to mobile has substantially diminished. It expects public service broadcasters to have uncontested access to DTT for at least the next ten years<sup>8</sup>.

Spectrum sharing would require both the broadcast and the mobile services to be transmitted from the same location. This means that sharing would be limited to the downlink from the base station – it would not include uplink from the handset – and the broadcast signal would have to be extended to mobile sites, at substantial cost.

In the absence of a clearly defined future for the UHF TV band, the additional network costs, and the limitation of sharing being restricted to the downlink, the case for spectrum sharing is very uncertain.

#### **2.1.5. Filecasting**

Filecasting is a technology proposed for downloading content to storage in the receiver for consumption sometime after transmission. Although this idea is not new, and storage costs continue to fall, we have not found evidence of any plans for such a service. This is probably due to the prevalence of OTT catch-up services, which more conveniently allow on-demand access to a much larger range of content.

#### **2.1.6. Rural broadband**

Two organisations we interviewed were interested in using spare capacity on a WiB network for delivering rural broadband. This would operate using standard fixed UHF TV antennas but may need the development of a new upstream path, as it is assumed that users would not be served by other broadband services. If mobile services were available it may be possible to use them for the uplink, while WiB could be used for the supplementary downlink. However, rural broadband networks using TV White Space spectrum have been possible in the UK for about three years, but as few networks have been installed there appears to be no good business case for doing this.

#### **2.1.7. Use cases summary**

In relation to improving SD and HD, the demand for WiB in Europe appears to be highly uncertain. Greater capacity for more SD and HD services may be better realised through the further adoption of more efficient transmission standards that are widely in use today e.g. DVB-T2/HEVC. Such an approach would not require the widespread change and viewer disruption that WiB entails. Additionally, IP systems such as HbbTV will continue to be developed and deployed to further enhance capacity capable of delivering these services.

Although yet to be quantified, it is also unlikely that any WiB enabled cost savings would outweigh the viewer disruption and infrastructure costs associated with the change, should they indeed be possible to realise. The potential cost saving aspect of WiB is not therefore seen as a source of demand in this context.

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<sup>7</sup> Public Service Broadcasting in the Digital Age

<sup>8</sup> Public Service Broadcasting in the Digital Age – Ofcom report

In relation to the introduction of new services such as UHD, filecasting, rural broadband, and spectrum sharing with other technologies, we have not identified sufficient demand that would require WiB.

## **2.2. Broadcaster interview responses on WiB**

Interviews were held with representatives of five European broadcasting organisations, with the objective of understanding their views about factors that could influence the commercial desirability of introducing WiB. The following section summarises our main findings. Due to frank responses, some interviewees requested anonymity, so this has been applied to all responses.

### **2.2.1. Introduction of UHD**

A new service offering is normally regarded as necessary for the introduction of non-backwards compatible technologies, so that consumers are motivated to buy the necessary new equipment. Widespread plans for providing UHD services might provide justification for the greatly increased capacity that could be made available by WiB networks, so broadcasters were asked about their views on introducing UHD to the DTT platform.

Organisations 1 and 2 said that they cannot imagine introducing UHD on the DTT platform. Advertising revenue is the same for SD and HD channels, and can be expected to be the same for UHD channels. Therefore, without a substantial increase in market share, the additional transmission costs cannot be justified. They foresee no demand for UHD on DTT in the future; UHD will be limited to home cinema, premium services and OTT, but not free-to-air DTT. They noted that demand for HD remains “disappointingly low”, and that SD channels are not pressing to migrate to HD.

Organisations 3 and 4 said that they currently have no plans for UHD, but this may change. One organisation is engaged in trials of UHD in a small number of cities.

Organisation 5 said that the introduction of UHD on the DTT network is a high priority. They are currently developing plans for the introduction of an additional multiplex to encourage the take-up of UHD, which would probably use DVB-T2 with HEVC.

### **2.2.2. Platform development**

Organisations 1 and 2 have invested a considerable amount of time developing ideas about how the DTT platform could develop, but they have not seen the need for WiB. The required investment to re-engineer the network for WiB might be of the order of €1bn, but the cost-benefit equation seems to be very unbalanced. Although they see linear off-air broadcasting as remaining strong for many years, development will focus on IP for catch-up and on-demand services. Further loss of spectrum for broadcasting could potentially give rise to the need for WiB to restore capacity, but WiB could only be considered in this case if the platform were still growing. Even then, expanding the IP side of their hybrid offerings may be more cost effective.

Organisation 3 operates in a country where 85% of channels are Pay TV, and where fibre is widespread, with about 30 IPTV operators. Market share for DTT is decreasing and is currently about 15%. They see the biggest risk to the DTT platform as spectrum loss, as political pressure will cause 5G to take priority over broadcast. The ability of WiB to share spectrum with non-broadcast services might enable continued use of at least some of the spectrum.



Organisation 4 operates 8 multiplexes, all in DVB-T, although there are trials of DVB-T2 in several locations. Market share of DTT is about 80%, but adding households using DTT for second and subsequent TVs brings this up to around 99%. There is a high level of fibre penetration, with ISPs offering bundles with TV. About 8% of households use IP for their primary TV. Development plans are focussed on increasing the number of multiplexes, possibly by making extensive use of Single Frequency Networks. Any loss of broadcast spectrum may stimulate interest in technological improvements available with WiB, but it is likely to be some years before this is clear.

Organisation 5 operates in a country where there are six multiplexes, all DVB-T. Plans are being developed for a seventh multiplex with about 70% coverage, after 700 MHz clearance, with the aim of encouraging the uptake of UHD, although they expect UHD will not bring any increase in advertising revenue. They see pre-loading advertising and on-demand content to local storage as drivers for increased capacity, but their priority is to improve services. They see bidirectional communications using WiB as of interest, with uplink capacity that is independent of mobile operators as desirable for rural broadband.

### **2.2.3. Summary of interviews**

Only one of the five organisations interviewed expressed a firm desire to introduce UHD onto their DTT platform. Two others were firm about not introducing UHD, and the remaining two were yet to decide.

Current long-term plans for development of DTT platforms do not appear to involve WiB, except possibly as a hedge against spectrum loss.

## **2.3. RSPG questionnaire on DTT deployments**

The RSPG has periodically invited frequency regulators from EU member states to respond to a questionnaire about the progress and plans that they have made for clearing the 700 MHz band in preparation for IMT use. Primarily the questionnaire is about the status of international frequency coordination activities underway in the respondents' countries, but it also seeks information relevant to this work. For example, it contains questions about the expected number of multiplexes after clearance, the physical layer and video compression standards that they will use and any plans for DTT.

The most recent questionnaire responses were compiled in January 2018<sup>9</sup>. While the responses contain a lot of helpful information, the questions were answered with a wide range of styles, ranging from very detailed to very brief. Similarly, at the time of responding, full plans for clearance had not been finalised in all countries. Some answers therefore reflect the anticipation of administrations, rather than a known outcome.

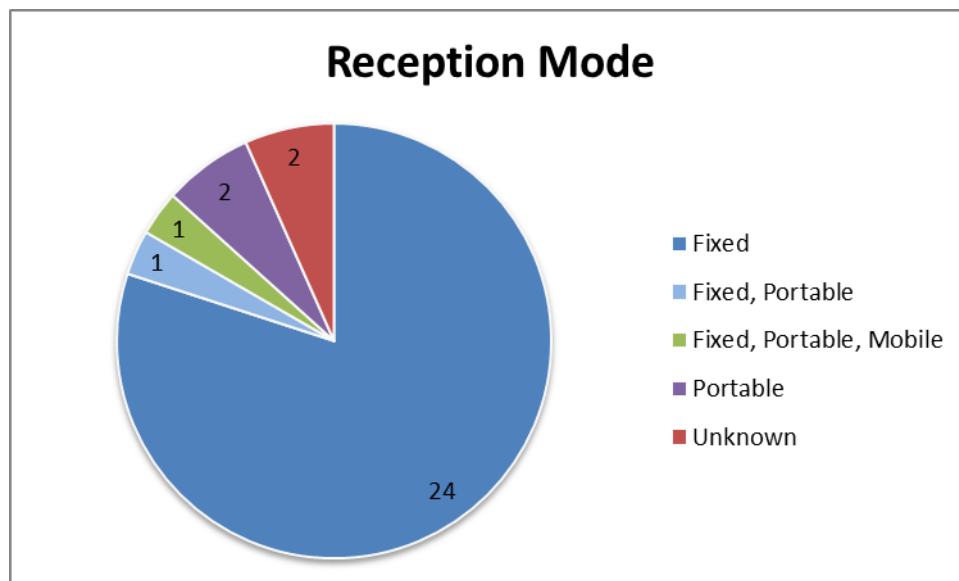
Bearing the above in mind, the main trends relevant for this work have been identified from the responses, and for simplicity, have been presented below from the viewpoint of 700 MHz clearance having taken place.

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<sup>9</sup> <http://rspg-spectrum.eu/2018/01/responses-to-the-4th-release-of-questionnaire-on-cross-border-coordination-regarding-700-mhz/>

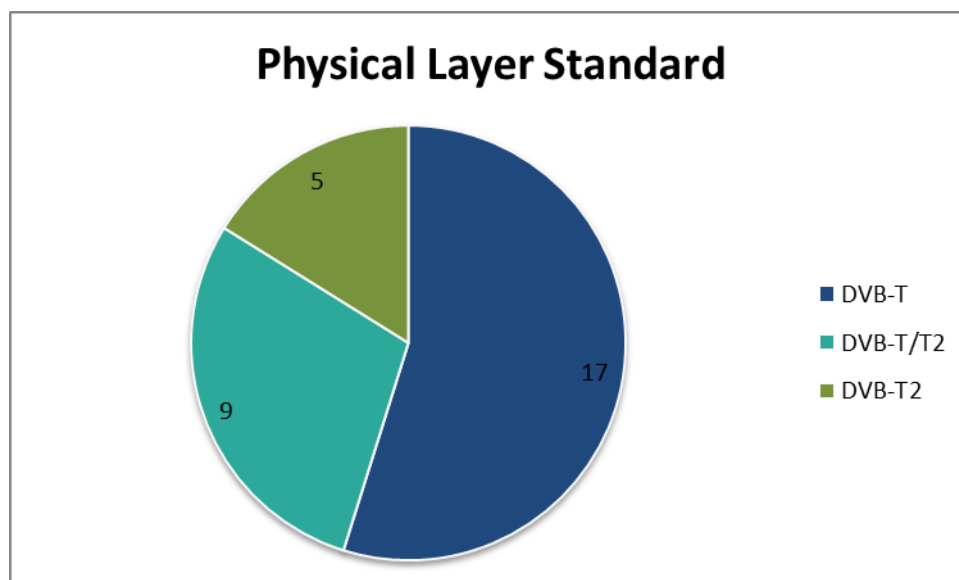
### 2.3.1. Reception mode

The DTT networks in the countries of almost all the 31 respondents rely on fixed external rooftop antennas for reception. Only two countries indicated that they rely solely on portable reception.



### 2.3.2. Physical Layer Standards Post 700 MHz Clearance

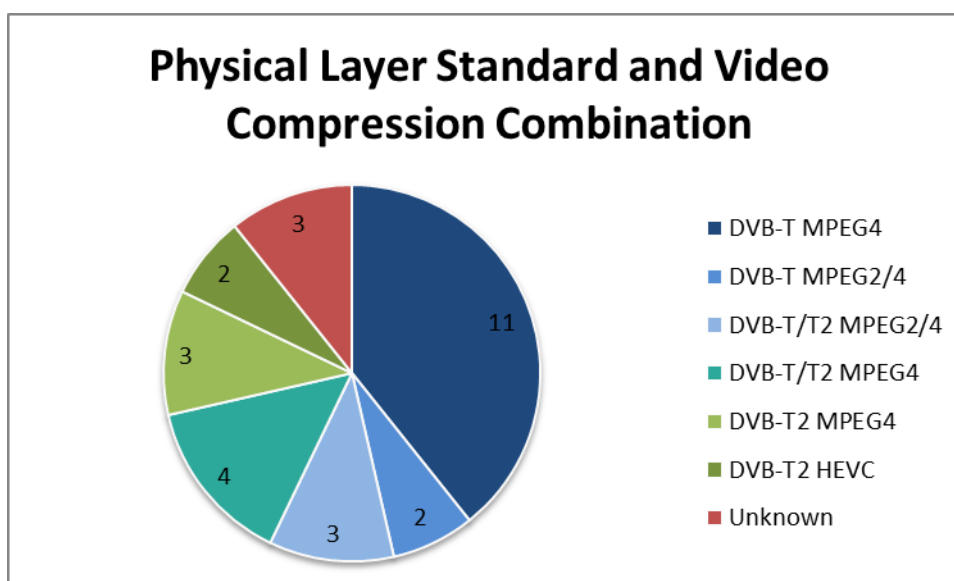
DVB-T will be used exclusively by 17 countries post 700 MHz clearance with a further nine indicating that they will have mixed DVB-T/T2 networks. Five countries (Austria, Germany, Finland, Netherlands and Romania) indicated that they will migrate entirely to DVB-T2.



### 2.3.3. Combined Physical Layer and Compression Standards

Of the 31 respondents only two countries (Germany, Netherlands) indicated that they will migrate to DVB-T2/HEVC at the end of 700 MHz clearance, or shortly thereafter.

Most countries (20) will use a combination of DVB-T/T2 and MPEG2/MPEG4.



#### 2.3.4. Other Observations

Several administrations indicated that it would be important to retain the present level of coverage after clearance.

Four countries highlighted the potential for UHD services in the future, but no firm plans were expressed.

15 countries have HD services on-air.

Some countries indicate that DVB-T2 will be essential for successfully implementing clearance, at least for some multiplexes.

#### 2.3.5. Summary of RSPG questionnaire responses

Most countries in Europe rely on fixed rooftop antennas for reception. WiB solutions that are compatible with existing receiving antenna configurations would therefore be more attractive for viewers.

In the short to medium term most countries in Europe will have the potential to expand their DTT capacity via the introduction of, or migration to further DVB-T2 HEVC multiplexes.

### 3. Migration paths

Ideally WiB services would be introduced in a clean-sheet environment where no consideration would need to be given to any existing transmission systems. However, as new frequency bands are unlikely to be available, any introduction of WiB would have to be within the spectrum already occupied by DTT services.

In circumstances such as these the introduction of WiB should therefore seek to:

- Minimise viewer disruption. Existing DTT services, both domestically and in other countries, should be able to continue substantially unchanged and unaffected so that they remain available to those who currently receive them, with their existing equipment.

- Offer attractive new content or services to a sufficiently high proportion of the population to drive uptake of, and encourage migration to, the new system.
- Minimise broadcaster costs both for maintaining the existing services while introducing the new e.g. where possible, significant reorganisation of the existing network should not be necessary.
- Allow different countries or markets to independently introduce WiB at a time that best suits them.

Two transition scenarios, which aim to satisfy the factors above, have been considered by TM-WiB. They are discussed and summarised below.

### **3.1. Migration path 1: Interleaved Spectrum**

This scenario investigated the potential to introduce a sub-national WiB service, aimed at covering the main population centres, interleaved with post-700 MHz clearance DTT services in UHF channels 21 to 48 (illustrated in Figure 4) – an approach analogous to the way low power DTT was originally introduced amongst analogue TV transmissions. The existing DTT networks would be left unchanged and WiB would have to protect them so that no harmful interference would be caused. Only those wishing to receive the new WiB-based content would therefore need a new receiver or receiving antenna.

Two studies were carried out based on the situations in France and the UK as examples of what may be possible. In neither case was an entirely satisfactory solution found.

The French study concluded that it would not be possible to introduce a viable WiB service in this way. Too much interference, causing the loss of existing services, would be caused.

The UK based study concluded similarly, although it also suggested a potential mitigation measure. If it were possible to convert the existing DTT network from DVB-T to DVB-T2 at the time of launching WiB, it may, at the expense of capacity, be possible to mitigate the interference. However, the potential loss of capacity would be around 51 Mb/s (the equivalent of more than one multiplex), which would have to be weighed against the potential for launching new services.

In both studies it was pointed out that further work would be required to determine whether such a scenario would be compatible with DTT networks in other countries.

The two studies based on this scenario indicated that it would be very challenging, if possible at all, to introduce WiB services covering a sufficiently high proportion of the population, in this way without causing significant interference, and therefore disruption to the existing DTT viewers.

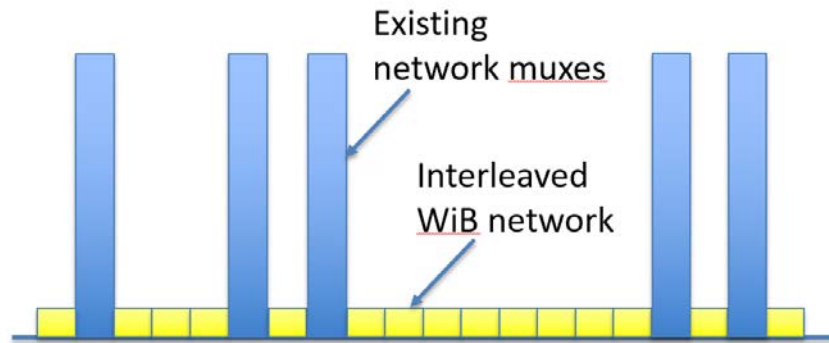


Figure 4 Illustration of interleaved DVB-T and WiB networks

### 3.2. Migration path 2: Backward Compatible DVB-T2 Extension

A second scenario may in principle be possible if the existing DVB-T2 standard were extended (i.e. a new standardisation). The introduction of backwards-compatible features could allow receivers to work with frequency reuse-1 planning, and with legacy receiving antennas. For example, additional pilot patterns could be added for interference cancellation along with new functionality for improved synchronisation.

The new backwards-compatible system, hereafter referred to as T2-WiB, would still use the traditional DVB-T2 bandwidth e.g. 8 MHz. At the same time the complete WiB standard (i.e. wideband) would be specified, so that new receivers could support both T2-WiB and (full) WiB.

Existing DVB-T2 transmissions would then be migrated to the new T2-WiB standard and be re-planned to use reuse-1 using one part of the UHF band (e.g. 2/3<sup>rd</sup>). As T2-WiB would be entirely backwards compatible with DVB-T2, existing DVB-T2 receivers would continue to work for a significant majority of the population and viewers would continue to receive their services. It is only in areas of interference, introduced by the move to frequency re-use 1, where a T2-WiB receiver would be required to receive a T2-WiB signal (note that no detailed work has been done to assess the significance of this requirement). The T2-WiB reuse-1 arrangement is shown by the yellow rectangle in Figure 5.

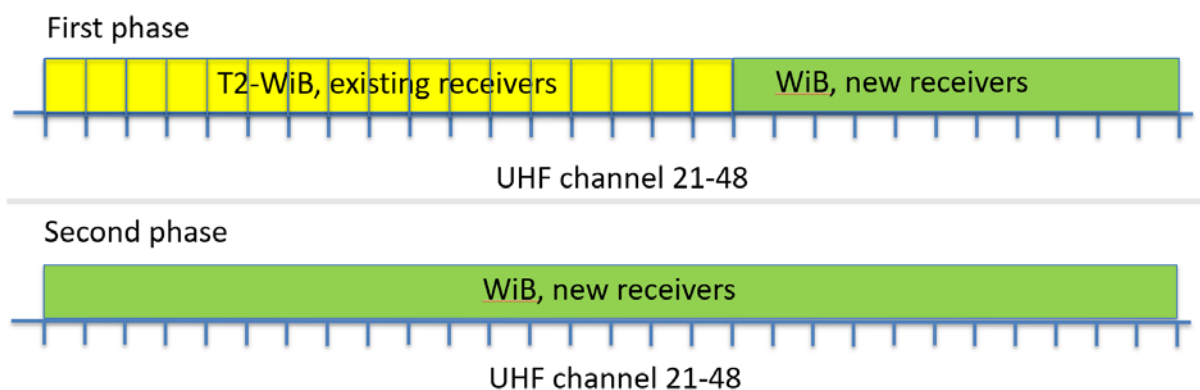


Figure 5 Illustration of T2 WiB and WiB deployment using FDD

For backwards compatibility with DVB-T2 receivers the T2-WiB services would continue to use their legacy video encoders, e.g. MPEG-2 or MPEG-4, at least initially.

In the remaining UHF spectrum (e.g. 1/3<sup>rd</sup>), WiB would be introduced using a more advanced coding standard, e.g. VVC. Due to the higher spectral efficiency of T2-WiB with reuse-1 and interference cancellation (where needed) it is possible (but not known) that all existing services could fit within a subset of the UHF spectrum, as outlined above. New, non-backwards-compatible services could then be introduced with WiB in the remaining part.

Over time, services could gradually move from T2-WiB to (full) WiB, at the same time adopting more efficient video coding with a corresponding capacity increase e.g. with a shift from MPEG-4 to VVC (assumed factor 4 in coding efficiency) one vacated T2-WiB service could be replaced by four (or likely more) WiB services, for a given quality. Gradually the entire DTT service could then move towards WiB and in the final stage all services would use WiB.

It is anticipated that a significant percentage of users would be unaffected by a change to T2-WiB. Among those that were affected, a relatively high percentage would benefit from a new receiver, which would solve the reception problem (caused by interference) and in addition allow them to receive the new WiB services (assuming they are attractive, e.g. UHD). Finally, there may be a small but significant number of users for which a new receiver would not be enough to avoid the interference. For these, a new antenna (conventional, but improved) is likely to restore reception.

Although this scenario may be technically possible, it must be stressed that it was only worked through in concept and remains subject to a more thorough investigation, including the potential disruption that may be caused to viewers. This scenario is however likely to require all countries, whose frequency plans interact, to simultaneously transition to T2-WiB in order to avoid undue cross-border interference, with viewers in affected areas needing new receivers. Elsewhere the full migration to DVB-T2 is assumed.

This scenario would not meet the third and fourth criteria set out above. It would involve significant costs for all broadcasters to maintain their existing services so that WiB could be introduced. It would also need relevant neighbouring countries to agree and move to new frequency plans in a coordinated way for both the first and second phases of Figure 5 – a very significant impediment that may prove impractical. Further work would also be required in order to determine whether this approach would be able to keep viewer disruption (i.e. replacement receiving antennas and receivers) to acceptably low levels in order to meet the first criterion above.

### **3.3. Migration cost aspects**

As the network modifications that the migration to WiB would entail are dependent on the circumstances of individual networks undergoing the transition, and the migration path chosen, it has not been possible to identify the costs of such changes in detail. Instead several aspects of the broadcasting chain, from video encoding through transmission and reception, which would involve change under WiB, and therefore incur costs, have been discussed below.

#### **3.3.1. Transmission networks**

Annex A describes examples of infrastructure changes that would be required to convert an existing transmission chain to WiB. It highlighted that almost all areas of the network would be affected, with the following equipment or systems potentially needing to be replaced:

- modulation and channel coding;

- multiplexing;
- video coding;
- high power amplification;
- distribution network;
- antenna;
- monitoring and control system.

Importantly, for the distribution network, careful thought would have to be given to relays as the current re-broadcast from main transmitters may not be viable with WiB, and as such line-fed relays would be needed at significant expense, see Annex A.

Although WiB entails substantial change (which should not be underestimated), the capex of a WiB transmitter network should be significantly reduced in comparison to the capex of building a new conventional DTT transmitter network. This is due to the simplified network architecture that WiB would make possible. For example, at each transmitter site only one amplifier would be needed for the entire WiB signal, from which it follows that no combiners would be required. In addition, the power consumption of a WiB transmitter network is reduced by about 90% compared to a conventional DTT network.

Offsetting these benefits is the likely need to write off the book value of existing networks, which may be substantial, for example given relatively recent re-engineering for switchover and 700 MHz clearance.

### **3.3.2. Receivers**

New receivers would be required for reception of WiB signals, for which the cost and disruption to consumers would have to be factored into any plans to deploy WiB. There are typically three models which can be considered for covering the costs of receivers:

1. The consumer pays the full market cost to buy the receiver;
2. The consumer pays a reduced price to buy the receiver, with the price being subsidised for example by the broadcaster or government;
3. The consumer is issued with a receiver as part of a subscription package, free of additional charges except perhaps an installation charge.

Little analysis is yet available of the manufacturing, development, IPR licensing, and testing costs of receivers for WiB. However, the introduction of new receivers would be expected to follow a typical consumer price curve.

### **3.3.3. Consumer antennas**

Most consumers should be able to receive WiB signals using their existing receiving antennas, as long as the network does not use dual polarisation. However, in some areas replacement antennas may be required, the supply and installation of which may significantly exceed the cost of the associated receiver. This could be a barrier to adoption of WiB receivers, especially without accurate prediction of locations where an antenna change would be required.

## **3.4. Summary of migration paths**

It is most likely that WiB could only be introduced within the spectrum already occupied by DTT. The two potential transition scenarios that were investigated revealed that it would be very challenging,

if possible at all, to introduce WiB in the post-700 MHz clearance spectrum while fulfilling the criteria set out above. Even when only considering compatibility with existing services, the two transition scenarios studied were found to be too challenging to be practical. Satisfactory transition scenarios therefore remain to be identified.

A summary of the main cost factors, potential capacity gains and network changes is given in Table 1 below. This highlights that for both migration path scenarios, the intermediate step to a full WiB network would require existing DVB-T/T2 networks to be extensively re-engineered. However, in principle (subject to development of the appropriate network equipment), most of the network changes could subsequently be used to fully migrate to WiB. The implications of such network changes should not be underestimated.

Scenario	Cost Comments	Capacity Gains	Network changes required for WiB – See Annex A for further details	Changes required to existing network
Migration path 1	Lower up-front costs	Moderate: There would be some loss of capacity in the DVB-T2 network. Overall, the interleaved WiB network will provide a net gain in capacity but WiB services would only be accessible to consumers with compatible receivers and would not provide full national coverage.	<ul style="list-style-type: none"> <li>- New video encoders and multiplexers</li> <li>- New wideband, medium-power transmitters</li> <li>- Potentially new antennas for WiB transmitter sites</li> </ul>	Existing networks would have to migrate to DVB-T2
Migration path 2	Higher up-front costs	Moderate: Potentially no loss of capacity for existing services. The new WiB deployment will provide an increase capacity but WiB network services will only be accessible to consumers with compatible receivers.	<ul style="list-style-type: none"> <li>- New antennas for WiB transmitter sites</li> </ul>	Existing networks would have to be converted to T2 re-use 1* to facilitate using a smaller portion of the available DTT spectrum. This would increase the number of muxes on air meaning that additional/new network infrastructure would be required

*Table 1 Summary of migration paths*

\*This would also require the DVB-T2 standard to be extended to allow a re-use 1 configuration.



## **4. What could happen if WiB wasn't introduced**

### **4.1. Scope for development of DTT without WiB**

There is a range of potential options for capacity improvement that may be available to operators of existing DVB networks. The extent of the options available will vary from case to case, depending on factors such as the encoding and modulation that is currently used.

#### **4.1.1. Encoders**

There are two options for encoders:

1. Most encoder vendors regularly make improvements to their encoders to ensure that they remain competitive. This means that a given picture quality can be achieved with increasingly lower bit rates. By upgrading their encoders within the standard they currently use, broadcasters may be able either to improve the average picture quality of their services, or to increase the number of services they carry. As the encoding standard is not changed in this process, services will continue to work with existing receivers.
2. As a rule of thumb, later generations of encoding standards (e.g. MPEG-4 compared with MPEG-2) roughly halve the bit-rate required for the same picture quality. This can provide a substantial increase in programme capacity, but usually at the expense of having to change receivers.

#### **4.1.2. Modulation**

There are two main options for modulation:

1. Increasing the FEC rate will give access to additional capacity at the expense of a reduction of coverage area (presuming that transmitter power cannot be increased). A change of FEC rate should be compatible with existing receivers.
2. Migrating from DVB-T to DVB-T2 will give rise to approximately 50% increase in capacity for a given transmitter power and coverage area. This change would not be compatible with existing DVB-T-only receivers.

Data shown in section 2.3 from the RSPG report shows that approximately 30% of European countries operate DVB-T alongside DVB-T2. In those countries the number of DVB-T-only receivers is expected to decline over some years, eventually reaching a point where a conversion to DVB-T2 may not cause undue viewer disruption. The capacity released could then be used for DVB-T2 multiplexes.

### **4.2. Consumer Equipment and Broadcast Technology**

This section considers the two sides of the broadcasting ecosystem, namely the receivers and the broadcast networks. Firstly, it considers likely developments and capabilities of consumer technology, it then considers broadcast transmission technology.

#### **4.2.1. Consumer Equipment: codecs**

Today's consumer devices contain a range of codecs and these are becoming increasingly advanced and numerous. Table 2 below summarises codecs either available or in development.

<b>Codec</b>	<b>Current status (2018)</b>	<b>Comment</b>
MPEG2/H.262	Ubiquitous deployment in CE devices	Used in many countries for linear broadcast services, usually in SD resolution, typically in the range 2-6Mbits/s <sup>10</sup>
MPEG4/H.264 AVC	Very widely deployed in CE devices	~50% bitrate reduction for the same picture quality compared with MPEG2 and used for delivering a mix of SD & HD services. The latter are broadcast in HD resolution at 8-10Mbits/s <sup>11</sup>
HEVC/H.265	In UHD TV only but likely to be increasingly common	~60% bitrate reduction for the same picture quality compared with H.264 <sup>12</sup> Some countries already broadcast using HEVC and there is an increasing receiver population in the market.
AV1	Not yet deployed but may initially be used more for online content.	This is a new codec and at the time of writing is not known to be deployed in consumer devices. Estimated 25% bitrate reduction over HEVC <sup>13</sup> adoption
H.266 (VVC)	In development	This codec is still being developed and is not deployed in consumer devices. Expectations for performance are in the magnitude of 50% bitrate reduction for the same picture quality over HEVC <sup>14</sup>

*Table 2 Key codecs suitable for use in consumer devices*

The availability of advanced codecs in receivers may make it more convenient for broadcasters to improve their service proposition with known technology.

However, for any upgrade model there is likely to be a legacy of incompatible receivers, particularly second or third TVs in a household, which may not be able to receive new services. These would also need to be considered.

## 4.2.2. Broadcasting Technology

### 4.2.2.1. Current DTT broadcast status in a few key DTT countries/regions

This section considers the broadcast technology used by some of the larger DVB (mainly European) countries/regions.

<b>Country</b>	<b>Systems</b>	<b>Comment</b>
Germany	DVB-T2 + HEVC (March 2017)	The DTT network is now well optimised
Italy	Migrating to DVB-T2 + HEVC by 2022	Is on the path to a more efficient DTT network

<sup>10</sup> Based on EBU report TR015: Defining spectrum requirements of broadcasting in the UHF band

<sup>11</sup> Refer to CM-T Long Term Vision Report

<sup>12</sup> Refer to TM-T MIMO study mission report TM-T0015

<sup>13</sup> CM-WiB0023\_Harmonics-view-of-the-future-of-video-coding

<sup>14</sup> CM-WiB0023\_Harmonics-view-of-the-future-of-video-coding

France	DVB-T + AVC (Switched in 2016)	Now looking at the feasibility of network enhancements with DVB-T2 and HEVC, possibly for UHD. The process has recently started
Spain	DVB-T + MPEG2	DVB-T2 trials are underway
Russia	DVB-T2 + MPEG4	In January 2015 Russia completed a transition from DVB-T to DVB-T2. MPEG4 was already in use
Nordic region	Mixture of DVB-T & DVB-T2 with AVC, some MPEG2 but limited.	There is a mix of services although a general trend is toward HD and beyond
UK	DVB-T + MPEG2 DVB-T2 + AVC, HD + SD	The UK system has been operating a mixed T/MPEG-2 + T2/MPEG4 since 2009.

Table 3 DVB deployments by region

#### 4.2.3. Potential network enhancement options for countries with legacy DTT broadcast systems

The previous sections have demonstrated that technical development will continue to happen in receivers and has also shown that a number of European countries are already optimising their DTT broadcast infrastructures to become more efficient, with some operators delivering or planning enhanced consumer services in return. For countries that have not yet made a complete migration to a DVB-T2 + AVC or HEVC environment there is considerable scope to improve efficiencies. However, there are many aspects to be considered before any such migration could be undertaken. Any network upgrade is very costly for an operator and they will naturally need to recover the substantial investment in their systems over several years as well as considering the impact on consumer equipment, consequently significant network upgrades only happen occasionally.

Other than optimising DTT networks it was suggested in the broadcaster interviews, see section 2.2, that in the future platform development could be catered for by expanding IP offerings to complement DTT services. Such a development strategy could minimise the prospect of upgrades to the DTT network or a move to new technologies such as WiB. However, a full transition to all-IP delivery remains unlikely for the next ten years at least<sup>15</sup> due to a range of technical and commercial barriers and the widespread use of DTT around Europe today.

Typically, changes are driven by a commercial need from the broadcast sector in conjunction with national regulators and potentially changes to national specifications.

Table 4 below considers some of the possible pros and cons of such upgrades.

Option	Pros	Cons	Efficiency + Capacity	Comment
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<sup>15</sup> Public Service Broadcasting in the Digital Age – Ofcom report

Keep current system: Do nothing (DVB-T / MPEG2, 64QAM 2/3, 6 multiplexes)	No significant investment It is possible that some small improvements with the current technology could be realised.	<ul style="list-style-type: none"> <li>- No service improvement</li> <li>- No efficiency improvements</li> <li>- Threats from Mobile</li> </ul>	No change e.g. circa 150Mbits/s with MPEG2	This is the least expensive and disruptive option but delivers no increased bandwidth optimisations or services
Reference system – all T2 (DVB-T2 256QAM 2/3, 6 multiplexes)	Increased capacity	<ul style="list-style-type: none"> <li>- Cost to convert transmitters to DVB-T2</li> </ul>	e.g. 240Mbits/s with MPEG4/AVC	There is a high proportion, but not 100%, of receivers that already support DVB-T2
DVB-T -> DVB-T2 migration	Improved spectral efficiency	<ul style="list-style-type: none"> <li>- Cost to upgrade</li> <li>- Low desire of some broadcasters to make further changes</li> </ul>	~50% bit rate reduction over DVB-T In the above scenario the capacity per Mux could increase from 24Mbits/s to 40Mbits/s	This would improve spectral efficiency and would ideally be coupled to a CODEC migration to say HEVC to give even better improvements
SFN migration	More efficient use of UHF spectrum	<ul style="list-style-type: none"> <li>- Cost to upgrade</li> <li>- Spectrum planning issues</li> <li>- Limited benefit in certain scenarios</li> </ul>	As per the study by EBU, TR029, the benefits of migrating to a national SFN alone may be limited compared to the cost/complexity involved.	Has been done in some Nordic countries but may not be practical due to cost and possible interference issues
MPEG2 -> MPEG4/AVC migration	<ul style="list-style-type: none"> <li>- Improved bitrate</li> <li>- Virtually all current receivers support this codec</li> </ul>	<ul style="list-style-type: none"> <li>- Cost to deliver/convert legacy programs to AVC</li> </ul>	~50% bit rate reduction over MPEG2	<ul style="list-style-type: none"> <li>- Use in conjunction with T2 Migration.</li> <li>- Scope for more services or HD services</li> </ul>

HEVC migration	Improvement in bit rate efficiency	<ul style="list-style-type: none"> <li>- Cost to re-encode/transcode legacy broadcast all content to HEVC</li> <li>- HEVC receivers are not yet universal</li> </ul>	This has been taken as an opportunity to deliver HD services more efficiently	This has been done in Germany in 2017, although in countries where DTT is the primary delivery mechanism a longer migration period is likely to be required.
Migration to a future codec such as VVC	These are expected to provide a further step improvement in efficiency	The codec is not yet deployed or in some cases even designed yet so significant questions about timing and product availability exist.	Significant improvements would be expected	To reach a significant portion of the population with deployed products this option is probably not realistic in the next 4-5 years unless driven by regulatory intervention. This scenario will naturally evolve over time.
IP delivery	IP can be used to supplement DTT services	Use of IP as a delivery path may make the business case for investing in a DTT network upgrade weaker.	It is not possible to quantify this	This may be used as a viable route to deliver more HD and even UHD services without investing in a new DTT network.

*Table 4 Pros and cons of DTT upgrade paths*

The expectation from continued optimisation of any DTT network will be a more spectrally efficient network where there is an increased capacity for the services from existing service providers. This capacity could potentially be used to enhance existing services with higher resolutions (for example more HD or some UHD), or to deliver a wider range of services or for some of the spectrum to be made available for new service providers.

For guidance, a potential improvement for a country migrating from DVB-T/MPEG2 to DVB-T2/HEVC would be expected to double the available bit rate and increase the number of programme services by a factor of 7-8<sup>16</sup>. This type of migration was successfully completed in Germany in 2017.

#### **4.3. Conclusion – if WiB were not to be introduced:**

Consumer equipment will continue to evolve mainly driven by requirements for rapidly evolving internet delivered services. This will be the case independent of whether broadcast services are changed.

There are in most cases significant gains to come from better utilising existing DVB standards and video codec improvements. This is highlighted by the recent DVB-T2/HEVC migration in Germany, providing 7-8 times more services compared with DVB-T/MPEG2.

### **5. Regulatory aspects**

Regulatory requirements are expected to continue to influence the evolution of the terrestrial broadcast platform. Whilst it is possible that the regulatory requirements in the future might be different from the present ones it has been assumed that:

- a) The regulatory and spectrum factors identified by the DVB CM-T group in the context of their study of a long-term evolution of terrestrial broadcasting will remain relevant, and
- b) Some regulation that is currently in place would need to be revised to allow WiB to be introduced in the UHF band.

#### **5.1. How could WiB enable terrestrial broadcast to meet the regulatory requirements in the future**

This section looks at how WiB could enable terrestrial broadcast to meet potential regulatory requirements in the future.

In *the Long-term Vision for Terrestrial Broadcasting (LTV-TB) Report*<sup>17</sup>, the CM-T group has identified three context factors of a regulatory nature that may have a significant impact on terrestrial broadcasting in the future. These factors are:

- spectrum reduction
- general interest objectives
- energy efficiency and environmental issues

Furthermore, for each of these three factors the expected impact on terrestrial broadcasting has been formulated.

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<sup>16</sup> Holger Meinzer, Lessons learned: Leapfrogging to DVB-T2 with HEVC in Germany, DVB World 2018

<sup>17</sup> A Long Term Vision for Terrestrial Broadcast, Study Mission Report of CM-T, available for download from [https://www.dvb.org/resources/public/whitepapers/cm1621r1\\_sb2333r1\\_long-term-vision-for-terrestrial-broadcast.pdf](https://www.dvb.org/resources/public/whitepapers/cm1621r1_sb2333r1_long-term-vision-for-terrestrial-broadcast.pdf)

Table 5 indicates those issues from the LTV-TB Report where WiB may be able to address the expected regulatory requirements.

The impact identified in the LTV - TB Report	How can WiB help?
<p><b><i>Spectrum reduction</i></b></p> <p><i>To provide future services within less spectrum the Terrestrial Broadcast networks should evolve towards:</i></p>	
<ul style="list-style-type: none"> <li>• <i>higher spectral efficiency</i></li> </ul>	<p>Spectrum efficiency could be significantly increased if the next generation of terrestrial broadcast networks and the receiving equipment were to be based on WiB.</p>
<ul style="list-style-type: none"> <li>• <i>increased resilience to interference from the adjacent bands (e.g. LTE) and within the band (e.g. white space devices)</i></li> </ul>	<p>In principle WiB may tolerate higher interference levels than the current DTT systems, although further work would be required in order to determine how effective it may be in practical operating conditions.</p>
<ul style="list-style-type: none"> <li>• <i>assessing if there is a role for Terrestrial Broadcast to play in serving or assisting consumption on mobile devices, which are largely stationary, and would be complementary to existing support through Wi-Fi offload</i></li> </ul>	<p>WiB networks can be configured for mobile coverage. The main scenarios that have been studied are intended for fixed roof-top reception from a High Power High Tower (HPHT) network, and therefore don't readily enable mobile coverage. However, it is still possible that WiB could be used in the context of a Low Power Low Tower (LPLT) cellular network to facilitate reception on mobile devices, perhaps with additional coverage being provided by the HPHT network. However, this scenario has not yet been studied.</p> <p>In addition, as WiB could be used in combination with LDM it is technically possible to provide services to fixed TV receivers and mobile devices at the same time.</p> <p>It should be noted that DVB-T2 networks could also be designed to provide mobile coverage but so far there was no market demand for such services.</p>

<b>General Interest Objectives</b>		
	<ul style="list-style-type: none"> <li><i>Because it is specially adapted to supporting public service objectives (e.g. national social and cultural objectives, maintaining continuity of information to the public even in emergency situations) Terrestrial Broadcast is very likely to remain in the very long term in many countries an important and highly desirable platform from the point of view of national authorities, in addition to its intrinsic reasons for resilience.</i></li> </ul>	Transition from DVB-T/T2 to WiB would not impact the ability of DTT networks to continue supporting general interest objectives.
	<ul style="list-style-type: none"> <li><i>In order to achieve this at minimum costs and with satisfactory quality it is very important for Terrestrial Broadcast to retain its ability to deliver a high volume of linear TV services but also to serve new applications. This would enable Terrestrial Broadcast to adapt to the evolving consumer demand and the needs of the service providers and retain a high reach in the public. Otherwise, Terrestrial Broadcast would be at risk of becoming an aging and non-competitive platform, unable to fulfil the important public objectives.</i></li> </ul>	WiB would enable substantially higher multiplex capacity than individual DVB-T2 multiplexes, hence potentially improving a business case for new services and applications such as HDR, UHD, to be delivered on the terrestrial platform.
	<ul style="list-style-type: none"> <li><i>National authorities should facilitate and encourage the technical evolution of the Terrestrial Broadcast and the integration of new services and applications, in particular through appropriate amendments to the regulatory framework.</i></li> </ul>	WiB may facilitate the technological evolution of terrestrial broadcasting. Some of the regulatory issues related to the introduction of WiB are covered in section 5.2 below.
<b>Energy efficiency and environmental issues</b>		
	<ul style="list-style-type: none"> <li><i>Terrestrial Broadcast is an energy efficient mechanism for delivering broadcast content to a large audience.</i></li> </ul>	WiB could substantially improve energy efficiency of terrestrial networks (e.g. 90% reduction in the overall transmission power).



*Table 5 Expected regulatory requirements, highlighted in the LTV-TB report, potentially addressed by WiB*

## **5.2. What regulatory changes would be required to allow introduction of WiB on terrestrial broadcast networks?**

As explained in section 1.3 the WiB approach would require international coordination, possibly on a large scale, to avoid cross border interference between new WiB networks and the existing conventional DTT networks. Beyond new frequency arrangements, coordination agreements may need to include conditions related to network synchronisation and dual-polar operation.

Within a country the introduction of WiB would require a new frequency plan, followed by new or revised network transmission licences, MUX licences, and the redistribution of MUX capacity. This, however, may be possible without changes to the existing regulation.

DTT receiver specifications would need to be updated.

New regulation might be needed to govern migration from the current DTT networks to WiB to support viewers that would need to upgrade their receiving equipment. Furthermore, mandating WiB in new DTT receivers as of a certain date might be considered to facilitate the transition.

Appropriate regulatory changes may be needed if new services other than TV (e.g. mobile or fixed broadband) were to be provided within the UHF band, whether over new WiB networks or otherwise facilitated by spectrum sharing capabilities of WiB.

## **6. Impact on secondary users of spectrum**

### **6.1. Use of TV broadcast spectrum for TVWS**

TV White Space (TVWS) is the term for technology which dynamically allocates access to unused UHF DTT spectrum (white spaces) enabling other communication services to utilise it. Such frameworks have been introduced in the US and UK, Canada, Singapore and Kenya<sup>18</sup>. Several companies offer TVWS hardware such as base stations and access points, allowing operators to provide applications including rural broadband<sup>19</sup>, video telemetry, smart city and IoT.

Technical field trials and small-scale commercial deployments have proved the technology works well, but with low-cost access points yet to be made available, large-scale commercial opportunities have so far been held back.

However, development in TVWS technology is continuing, and this could lead to a reduction in manufacturing costs to a scalable level. The use of TVWS therefore remains a technically workable contributor to broadband connectivity, particularly in hard to reach rural areas and some commercial services exist.

The introduction of WiB would effectively eliminate the market for TVWS services, which although

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<sup>18</sup> <http://dynamicspectrumalliance.org/pilots/>

<sup>19</sup> <https://www.arranbroadband.com/about-1>

currently very small, is being used for commercial services and the impact to these would need to be considered.

## **6.2. Use of TV broadcast spectrum for PMSE**

PMSE audio wireless applications operate predominantly in the UHF band as secondary spectrum users which mean that they must not cause harmful interference to TV services nor can they claim protection from TV transmissions. In practice, PMSE applications currently operate in those UHF frequency channels that are locally unused for DTT.

The amount of UHF spectrum available for PMSE applications has been reduced due to the clearance of the 800 MHz band from TV services in recent years and will be further reduced by the ongoing clearance of the 700 MHz band. In both cases the remaining part of the UHF band has been re-planned to accommodate the DTT services which had to be removed from the cleared bands. In any new frequency plan, the DTT services will be more tightly packed than before the clearance and, as a result, the amount of spectrum still available for PMSE applications is decreased. The impact on PMSE operations is believed to be significant only at large special events, studio complexes, production facilities and theatres where the highest number of PMSE devices (50 or more) is in use at the same location.

However, there is a growing concern that any further reduction in spectrum would result in serious constraints not only on the large content applications previously mentioned but also on broadcasters' day-to-day operations. Regulators have identified some additional alternative frequency bands that could be used for PMSE and are investigating further candidate bands that might be made available to PMSE users in the future. This non-UHF spectrum is in disparate bands and collectively totals only about 30 MHz (or 80 to 90 MHz if an additional band 960-1164 MHz is agreed) and PMSE equipment which supports these bands has, at best, patchy availability.

If WiB were to be introduced in the UHF band with re-use 1 this would further reduce or almost eliminate the available UHF spectrum for PMSE, depending on the deployment scenario.

The severity of impact on PMSE would strongly depend on the scenario and the timing of WiB deployment. The negative impact could be mitigated if a sufficient suitable alternative spectrum is available to which the PMSE users could migrate and there was equipment available that supports that spectrum. However, such migration might be challenging since PMSE users are diverse and numerous and, in some countries, subject only to a general authorisation i.e. no individual license is required. This also makes it difficult to assess the number of users that are likely to be affected and the amount of equipment to be replaced.

In commercial terms, taking the UK only as an example, the creative industries are responsible for a contribution of £92bn p.a.<sup>20</sup> to the economy and it can be assumed that the largest users of PMSE applications, who would be most impacted, contribute most of this sum. In terms of equipment quantity and value, a report commissioned by the European Commission estimates that there are

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<sup>20</sup> "Creative industries' record contribution to the UK economy" [ref <https://www.gov.uk/government/news/creative-industries-record-contribution-to-uk-economy>]

around 2 million wireless PMSE links which would have to be replaced at a total cost of €10bn, subject to like for like equipment pricing and equipment suitability and availability<sup>21</sup>.

## 7. Timings

Before DVB could embark on developing a standard for WiB, two significant concerns would have to be dealt with:

1. At present, it appears that coordination of national networks may not be able to be achieved in a way that permits the full gain of a WiB network to be realised, see section 1.3.
2. The business case for proceeding does not currently appear to exist.

The time taken for resolving coordination is not bounded, and there is no guarantee of success. Similarly, the business case for proceeding may not appear at all, and if it does, it is impossible at this stage to say when.

If the current situation changes, removing the two barriers described above, DVB may then wish to proceed. In this event we estimate that a period of 3-4 years may be required between starting work in DVB and receivers becoming available. We recommend that DVB members should review the barriers as and when there are significant changes in the broadcasting landscape.

## 8. Conclusions

While in principle the use of WiB could in most cases enable very significant increases in network capacity, several commercial factors appear to make the case for WiB insufficiently compelling:

- there is little demand for WiB in the context of the use cases we have studied (more or better-quality SD and HD TV content, introducing UHD TV, reducing network costs, spectrum sharing, filecasting, rural broadband);
  - additionally, for most countries in Europe there is potential to increase the capacity of DTT networks within existing DVB and video encoding standards, or by developing and extending hybrid services over IP, at considerably less cost and disturbance than implementing a WiB network.
- the reduced network costs do not warrant the costs of implementing new networks and writing off existing networks;
- implementation of networks would have to be on a harmonised and coordinated basis among neighbouring countries, which would be very difficult to achieve;
- migration paths would be costly to implement;
- consumers would have to purchase new receivers;
- there would be a serious impact on other users of the spectrum, particularly PMSE (Programme Making and Special Events) and TVWS (TV White Space);

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<sup>21</sup>Assessment of socio-economic aspects of spectrum harmonisation regarding wireless microphones and cordless video cameras (PMSE equipment), Final Report, A study prepared for the European Commission DG Communications Networks, Content & Technology Valdani Vicari Associates (VVA) Consulting, 2013 <https://ec.europa.eu/digital-single-market/en/news/report-assessment-socio-economic-aspects-spectrum-harmonisation-regarding-wireless-microphones>

The CM-WiB Study Mission has therefore concluded that there are insufficient grounds to recommend developing WiB further at this time within DVB. However, we recommend that from time to time DVB should re-examine this situation, for example if the broadcasting landscape changes.

## Annex A DTT network changes required for WiB

### Existing Network Architecture

To better understand how a WiB network may be deployed, it may be useful to consider it in the context of how DTT networks are commonly architected today.

For the purposes of this document, Figure 6 shows the main components in a transmission chain of a DTT network typically on-air today. On the left-hand side of the figure various content providers make their content available to encoding and multiplexing centres where a number of programmes are compressed and combined into multiplexed streams of content<sup>22</sup>. The streams are then sent out over a distribution network to the transmitter sites where one transmitter modulates and amplifies the signal of a single multiplex ready for transmission. Combiners are then used to combine multiple RF signals from the transmitters before they go into the antenna system for transmission. Note that for simplicity the diagrams below show only one of the many transmitter sites comprising a full network.

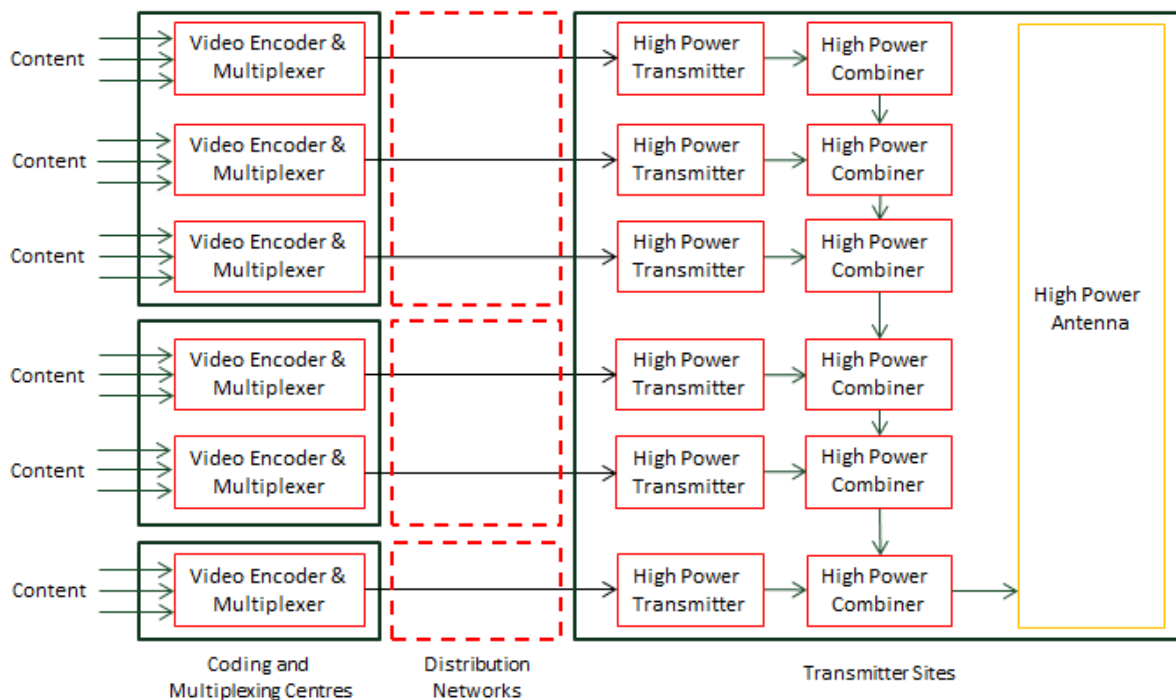


Figure 6 Example of existing DTT distribution network

<sup>22</sup> Although the diagram shows the common, and general case of multiple coding and multiplexing centres it is also common for all this functionality to be consolidated in a single location.

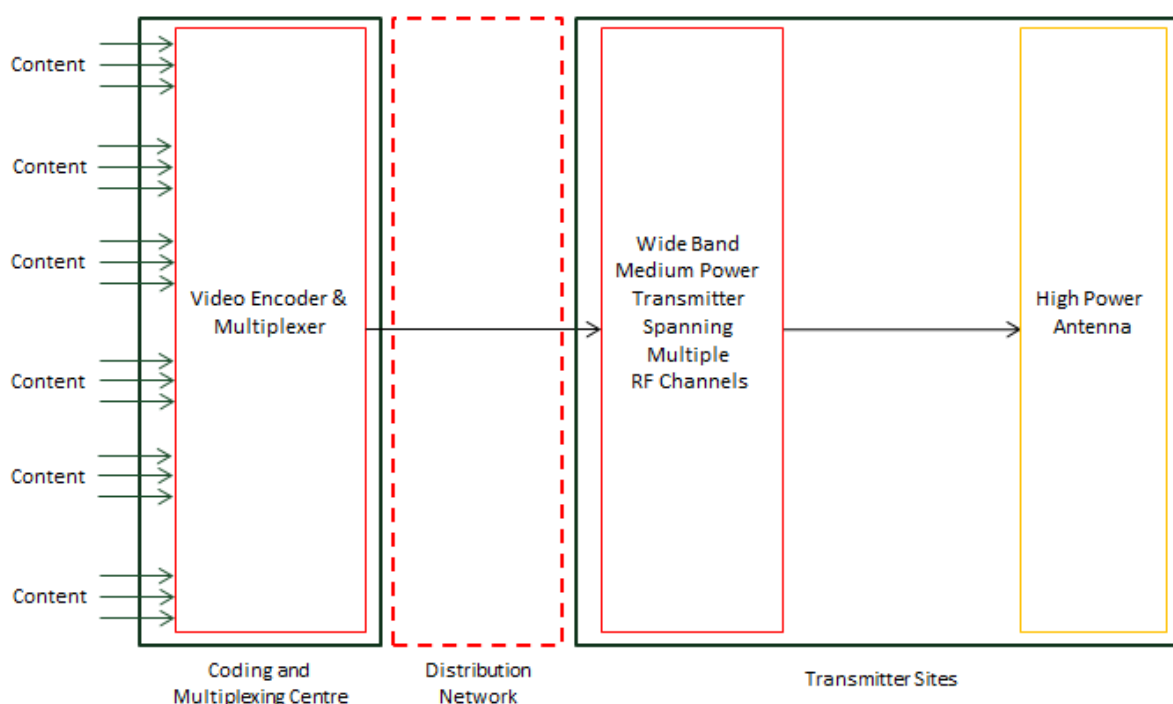
## WiB Network Architecture

Although there are several ways in which WiB could be deployed, two pragmatic examples are illustrated in Figure 7 and Figure 8. The most spectrally efficient example, and conceptually the simplest, is set out in Figure 7. It could be the ideal scenario in which the widest (and highest capacity) transmission channel is made available to maximise statistical multiplexing gains and coverage benefits (derived from the greatest available frequency diversity).

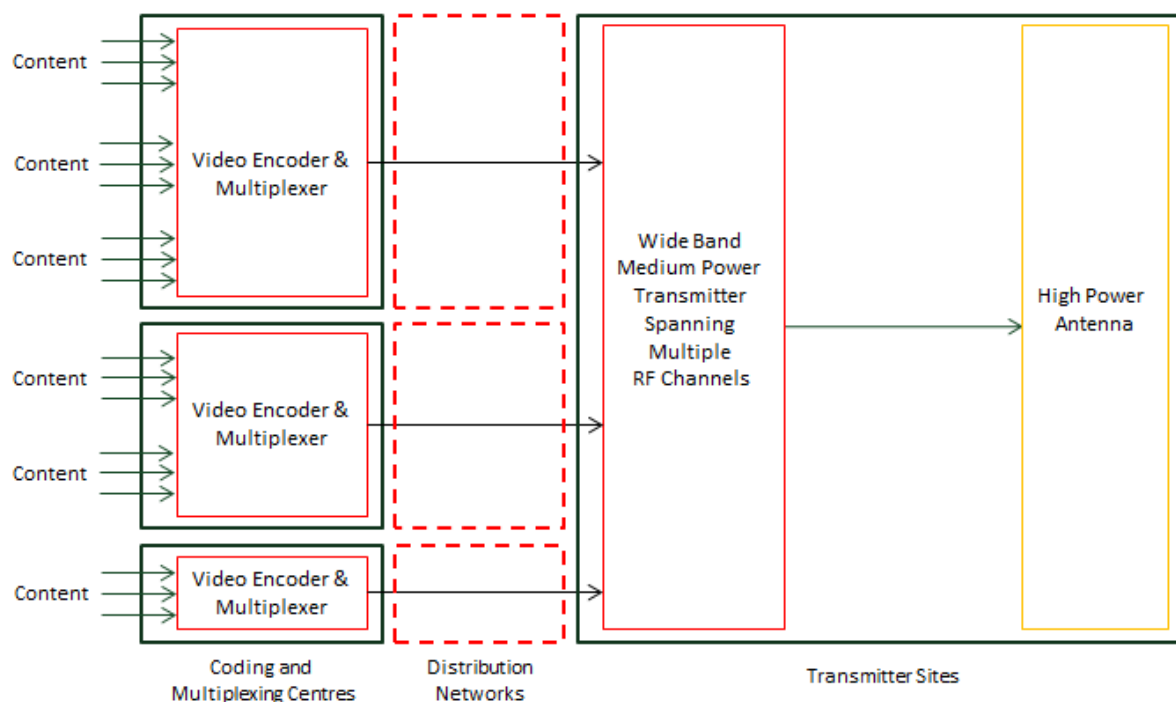
While Figure 7 may represent the ‘ideal’ scenario, alternative arrangements may be better suited to the practical, commercial and regulatory circumstances at hand for a given deployment. For example, distinctly separate coding and multiplexing arrangements may be attractive, as is common today. Figure 8 shows one way in which WiB may be deployed to achieve an architecture such as this.

In whichever way WiB may eventually be deployed, and under the assumption that it would be introduced with higher capacity services than previously existed, the red boxes in each of the figures show the areas of the network that would either need to be upgraded or replaced upon the introduction of WiB. The orange boxes show areas that may need to be changed.

As should be clear, unlike the upgrade from DVB-T to T2, for example, WiB would constitute considerable change to the way networks are currently architected, and therefore to the equipment with which they operate. The following sections provide more background on how each area of the network may change relative to a DVB-T/T2 network on-air today.



*Figure 7 WiB Distribution chain with consolidated coding and multiplexing centres*



*Figure 8 WiB distribution chain with multiple coding and multiplexing centres*

### Coding and Multiplexing

Due to the higher capacity involved with WiB, it is likely that new coding and multiplexing equipment would be needed. This would be particularly true if the consolidated coding and multiplexing approach was adopted in circumstances where it was not originally done in that way. However, WiB would be sufficiently flexible to allow coding and multiplexing to either be carried out in a single, common location (Figure 7), or in independent (i.e. geographically and commercially) centres (Figure 8). WiB could therefore ‘slot in’ with existing arrangements if that was most practical.

### Distribution

Should the capacity of the multiplexes increase it would also be necessary to commensurately increase the capacity of the distribution network to match.

Additionally, careful thought would be needed for distribution to relay transmitters (or transposers). Normally in DTT networks a significant proportion of the lower power sites take an off-air feed, transpose the signal to a different RF channel and then re-transmit it. These relay transmitters significantly reduce the operational and capital cost of networks as they require no dedicated programme feed – they simply re-broadcast an off-air signal from another station.

As with on-channel repeaters today, relay transmitters in a WiB network operating over the entire allocated spectrum may need dedicated feeds as it would not always be possible to transmit on the same RF channels as are received.

The TM study mission report identifies a tentative solution, indicating that if no more than half of total available capacity is allocated to services requiring relays then off-air feeds may remain viable. However, this requires further study and it should be noted that if no solution is found then dedicated feeds to relays would constitute significant additional cost.

Other parts of the distribution network, such as T2 gateways would also require replacement.

## Combiners

In most cases it is expected that WiB would no longer require combiners. At each site a single wide-band transmitter, covering the entire UHF band, would be proposed. Thus, the need for combiners would be obviated.

In conventional architectures the combiners perform the additional function of filtering. No work has been done to determine how wide-band WiB transmitters would meet the requirements for out of band emissions in the absence of such filtering.

It is not, however, a strict requirement to operate a single wide-band transmitter. If it were more practical, multiple transmitters, each spanning more than one RF channel, could be combined in a similar fashion to today. New, wider band combiners would however be required in that case.

## Transmitters

In most cases it is expected that individual transmitters would no longer be required with WiB. At each site a single wide-band transmitter, covering the entire UHF band, would be proposed.

Furthermore, section 1.2.1 indicates that it is expected that total power needed for the new wide-band transmitter would be lower power than a single high-power transmitter in today's DTT networks.

## Antenna

The antenna systems would need to be checked in order to confirm that they operate sufficiently well on all the channels that WiB would use. Although modern antenna systems are generally capable of operation over the entire UHF band, some older or bespoke systems may have a more restricted range. Furthermore, some networks may operate a 'banded' nature of transmissions where the frequencies in operation at particular sites are restricted to a relatively narrow portion of the UHF band. In such cases the satisfactory operation of the antennas would need to be checked for suitable WiB performance.

In the case where WiB would be deployed with multiple transmit polarisations it is likely that essentially all transmitting antennas would have to be replaced.

## Summary

Compared with existing DVB-T/T2 network architectures, WiB constitutes significant change - it touches on all aspects of the network. A full migration to WiB from an existing DTT network would therefore involve the upgrade or replacement of much of the existing infrastructure.

## Glossary/definitions

A/V	Audio and Video
ABR	Adaptive Bit Rate
AV1	Alliance for Open Media, Video 1, a new video coding format
AVC	A video coding standard also known as H.264 or MPEG-4

CM	Commercial Module within DVB
CM-T	The DVB terrestrial sub-group of the Commercial Module
CM-WiB	The DVB WiB study mission sub-group of the Commercial Module
DASH	Dynamic Adaptive Streaming over HTTP
DTT	Digital Terrestrial Television
DVB-I	A proposed DVB standard for carrying content over the Internet
DVB-T	The first-generation DVB standard for terrestrial coding and modulation
DVB-T2	The second-generation DVB standard for terrestrial coding and modulation
EBU	European Broadcasting Union
FEC	Forward Error Correction
HbbTV	Hybrid Broadcast Broadband TV
HD	High Definition
HEVC	High Efficiency Video Coding, also known as H.265
HPHT	High Power, High Tower
IBC	International Broadcasting Convention
IoT	Internet of Things
IPTV	Internet Protocol TV
ITU	International Telecommunications Union
LDM	Layer Division Multiplex
LPLT	Low Power, Low Tower
LTV-TB	Long Term Vision report for Terrestrial Broadcasting
Mbit/s	Megabits per second
MFN	Multi-Frequency Network
MIMO	Multiple Input Multiple Output
MPEG-2	Motion Picture Experts Group 2, an early generation video coding standard
MPEG-4	A video coding standard also known as H.264/AVC
OTT	Over-The-Top, meaning carried on the unmanaged Internet
PMSE	Programme Making and Special Events, typically audio links
QPSK	Quadrature Phase Shift Keying, a robust modulation format for data
RF	Radio Frequency
RSPG	Radio Spectrum Planning Group
SB	Steering Board within DVB



SD	Standard Definition
SFN	Single Frequency Network
TFS	Time and Frequency Slicing
TM	Technical Module within DVB
TM-WiB	The DVB WiB study mission sub-group of the Technical Module
TVWS	TV White Space
UHD	Ultra-High Definition
UHF	Ultra-High Frequency
VVC	Versatile Video Coding, a successor standard to HEVC
WiB	Wideband broadcast re-use 1
WRC	World Radio Conference



# **Technical Review of WiB**

## **TM-WiB Study Mission Report**

**June 2018**

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**Wideband Frequency Re-use 1 (WiB)**  
**Final report of the DVB Technical Module**  
**Study Mission Group (TM-WiB)**

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**Wideband Frequency Re-use 1 (WiB)**  
**Final report of the DVB Technical Module**  
**Study Mission Group (TM-WiB)**

**1. Executive Summary**

Following the publication of an IBC paper in 2016 on WiB [1], DVB commissioned two study mission groups, one commercial and one technical, to evaluate the technology and its potential for adoption by DVB. This report is the final report of the technical group, TM-WiB.

At its heart, the WiB concept aims to dramatically reduce the terrestrial broadcast transmitter operating power requirements (typically by around 90%), by reducing the system operating point from using a high order modulation scheme to a much more rugged low order modulation. The reduction in capacity is compensated by an increase in bandwidth, but this still results in a significant overall saving in transmitter power requirement. Another consequence of the increased bandwidth is that all the transmitters in a network need to use the same frequencies, hence it is referred to as frequency re-use 1. The lower order modulation means signals are much more robust against interference, but interference cancellation techniques would also need to be used.

As well as allowing for significantly reduced transmitter power, which in turn brings the potential for a significant saving in transmitter capital equipment (including perhaps removing the need for high-power combiners), WiB has the potential to provide an increase in spectral efficiency, allowing a higher capacity within the same RF bandwidth. This aspect has been the focus of much of the study within the TM-WiB group, as well as the extent to which any potential gains may be realisable.

The main results from this part of the study conclude that whilst the predicted power saving is indeed realisable, the benefit in terms of spectral efficiency gain depends very much on the assumed starting point of the network. In some scenarios, for example in Italy, where current planning is already on the basis of frequency re-use 2 due to the shielding effect of the surrounding mountains and the larger distances to neighbouring countries around the Mediterranean Sea, it is expected that the introduction of WiB would result in a significant loss of spectral efficiency, and so would not be appropriate. Detailed network planning studies have been undertaken only for the UK. In this case there is a potentially worthwhile efficiency gain for WiB, although the size of the gain depends significantly on the assumed starting point for the comparison (a direct like-for-like is not possible with the current MFN situation comprising a mixture of multiplexes with differing levels of coverage). The gain would be reduced if instead the comparison was done against a regional SFN, and perhaps further reduced comparing against a mixture of national and regional SFNs, but these comparisons have not been studied in detail.

Furthermore, in the time available it has not been possible to undertake practical system simulations, so the extent of any potential gains have not been verified, and they may in practice prove to be considerably reduced.

Whilst at face value, if the largest potential gain were fully realised, it might be attractive for High Power High Tower (HPHT) networks in a like-for-like system change (as was the case when moving

from DVB-T to DVB-T2), WiB involves much more than a like-for-like change. WiB would require a significant change of approach to planning which could be very difficult to coordinate across Europe, and the gains would only be realised if it was widely or universally adopted, since transmissions between all neighbouring countries need to be synchronised.

Another issue is how WiB could be introduced into an existing DTT environment. Although options for transition scenarios have been identified, when WiB needs to coexist with current DTT signals, the benefits are significantly reduced, making the introduction particularly difficult.

Overall, whilst the possibility for a dramatic transmitter power reduction has been confirmed, any potential capacity gains for WiB would require further verification with detailed system implementation and planning studies. Depending on the starting scenario, implementing WiB could provide a worthwhile gain in capacity or a loss, but any gains need to be considered very carefully against the scale of the network changes required, particularly including the complexity of transition, and receiver implementations required.

A considerable amount of technical work has been undertaken during this study, and this report provides some detailed descriptions of that work. For those readers only interested in a relatively brief overview, it is recommended to concentrate on the introduction to WiB concepts in section 2, the networks studies in section 4, the results and discussion in sections 5 and 6 and the conclusions in section 9.

As well as this main part of the study the group has also considered several supporting technologies that would either need to be introduced alongside WiB, or are enhancements to the basic WiB concept. These are described further in section 7.

## **2. Introduction to WiB concepts**

The WiB concept was first formalised by the publication of the IBC 2016 paper [1]. DVB commissioned both technical and commercial study missions (TM-WiB and CM-WiB respectively) to investigate the ideas proposed in [1], which used that as a starting point, but have inevitably considered several related concepts during their work. This document is the final report of the TM-WiB group.

### **2.1. Fundamental WiB concept – Wideband transmissions, frequency re-use 1**

TM-WiB have assumed as a starting point the use of a traditional High Power High Tower (HPHT) television broadcast transmission network; these typically carry high data rate services using DVB-T or DVB-T2, and are often configured to operate as multi-frequency networks (MFN's), with a frequency re-use factor of around 5 – in other words around 5 UHF channels are required to carry one group of services in a single DVB-T or DVB-T2 multiplex, with different channels being used in different geographical areas to avoid interference. (Alternatively, regional single frequency networks (SFN's) can be used, where a single frequency is used throughout one area, but often the frequencies used would need to be different between adjacent areas, again to avoid interference, and ultimately over a large area a similar order of frequency re-use may well be obtained.)

Whilst high order modulation might be used on any one channel, e.g. 256-QAM with a code rate of 2/3, which has a raw spectral efficiency of 5.3b/s/Hz, the re-use factor of 5 means that the overall

spectral efficiency is reduced to around 1b/s/Hz, especially after considering overheads such as guard intervals, reference pilots and signalling requirements.

The basic WiB concept introduced in [1] proposed instead to use much lower order modulation coupled with a frequency re-use factor of 1, which would mean the same channels being used in all areas, to achieve a similar result. The lower order modulation means signals are much more robust against interference, but interference cancellation techniques would also need to be used – these are discussed in more detail later in this report. The loss of capacity from the lower modulation mode is compensated by using a wider bandwidth channel. The first main advantage of doing all this is that it allows a significant overall reduction in transmitted power, because of the characteristics of the Shannon formula. This gives the relationship between the theoretical capacity ( $C$ ) available in a channel and the receiver's signal-to-noise ( $S/N$ ) ratio:

$$C = B \cdot \log_2 \left( 1 + \frac{S}{N} \right), \text{ where } B \text{ is the bandwidth of the channel.}$$

From this we can see that to maintain a constant capacity, if  $S/N$  is reduced, the bandwidth must be increased, but the presence of the 'log' term results in a very favourable trade-off. For example, if the required  $S/N$  is reduced from say, 18dB to 1dB, the bandwidth only needs to be increased by around a factor of 5. Hence an overall reduction in transmitted power of 10dB is obtained. In other words, a group of 5 UHF channels, being used in an MFN with re-use 5, could conceivably be replaced by a wideband transmitter, operating across all 5 channels at every site (i.e. frequency re-use 1), with a total power of just 1/10 of the original, and delivering the same total capacity (i.e. an overall spectral efficiency of around 1b/s/Hz). This is illustrated in Figure 1.

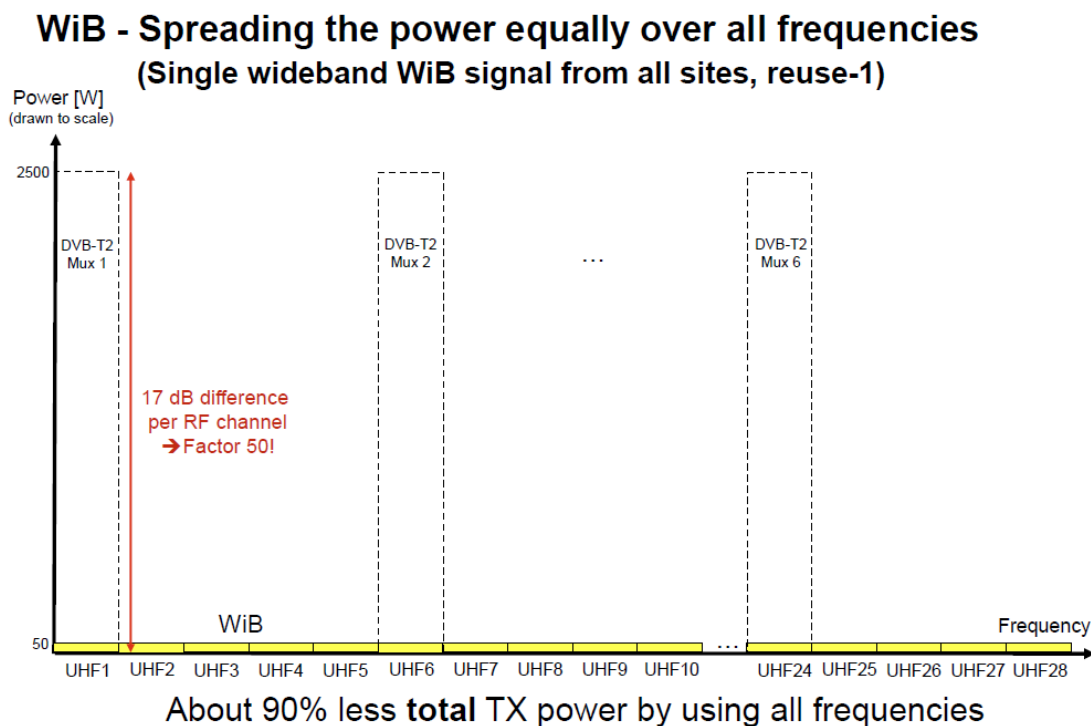
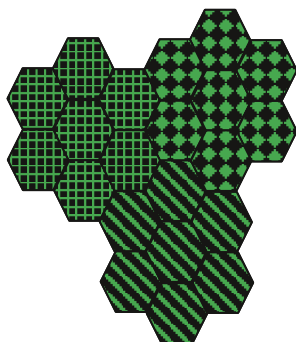


Figure 1. Illustration of wider bandwidth but reduced total power for WiB



## **2.2. Scope for increased capacity**

TM-WiB has additionally considered whether the WiB concept might also allow for significantly increased capacity. One approach which appears in theory to be able to achieve around twice the capacity (e.g. around 2b/s/Hz), is by using groups of transmitters operating together to carry the same signals (in a traditional SFN), with adjacent areas (carrying different signals) operating on the same frequency. For example, in the network below, each of the cells with the same shading are operating in an SFN (i.e. carrying identical signals).



## **2.3. Comparison with other approaches**

TM-WiB has also considered whether there might be similar approaches to that described above that do not require the use of interference cancellation but might also achieve increases in capacity. Two such potential approaches have been identified – either using a traditional MFN but with re-use factor of around 3; or by using re-use 1, but with enhanced antenna performance to help eliminate the interference and therefore avoid the need for interference cancellation. If this latter approach is feasible, it could potentially be applied to existing systems such as DVB-T2.

## **2.4. Layer division multiplexing (LDM)**

If WiB is being used, and receivers are employing interference cancellation techniques, they would also potentially be capable of decoding an LDM signal. For this, two (or more) signals are transmitted together, with one more robust signal ‘on top of’ a less robust one. The more robust layer must be decoded first, and then cancelled to allow decoding of the lower layer.

## **2.5. Scenarios**

This section briefly describes the network and reception scenarios considered by the group.

### **2.5.1. Fixed roof-top reception from HPHT network**

The main scenario considered by TM-WiB assumes that a conventional HPHT network is replaced with reduced power transmitters operating from the same sites, and targeting approximately the same coverage areas, generally implying reception on traditional fixed roof-top antennas, to provide broadcast network services that are broadly similar to today’s terrestrial TV networks. The network planning approaches that were considered are discussed in more detail in section 4.

### **2.5.2. Reception with hand-held devices**

The group considered whether WiB might also allow greater coverage to hand-held devices from a HPTP network. However, the link budget in this case is particularly unfavourable (typically an additional 50dB median path loss for indoor suburban reception), and the more robust modulation used for WiB would not be able to compensate for this. The group therefore ruled this scenario out from its consideration, early in the studies.

An approach that may prove more practical is the use of WiB in a more dense, Low Power Low Tower (LPLT) cellular network, to provide broadcast coverage to mobile devices. Whilst the detailed results from the studies in this report have focussed on the traditional fixed roof-top case, and therefore cannot be generally applied to the LPLT mobile case, the same general principles would still be expected to apply. A further variant that may also be of interest in this scenario is the use of LDM to allow transmission of a robust broadcast upper layer together with a lower layer targeting unicast services. Devices close to the centre of the cell would have sufficient additional noise margin to allow reception of both layers, whereas devices at the edge of the cell might only be able to receive the broadcast layer. However, the omni-directional antenna of the mobile device would impact the achievable capacity at the edge of the network, compared to a directional roof top antenna.

Detailed study of these areas has not been undertaken, not least because it was agreed that any standardisation work that was required in this area would be best undertaken within 3GPP.

### **2.5.3. WiB with downlink-only LDM for rooftop reception**

In TM-WiB0089 KTH and Teracom report about a theoretical study they have performed about joint spectrum use of broadcast and unicast using LDM and Massive MIMO. The foreseen use case is broadcast and broadband (unicast) transmission from High Towers with rooftop reception using a roof-top directional antenna, which could receive both the broadcast and broadband signals.

A traditional broadcast network (cell radius 30 km) was assumed with WiB broadcast as a basis and with a lower LDM layer from the same sites and in the same spectrum (i.e. same time & frequency).

Exploiting the possibilities for very large transmitting antennas (perhaps as large as 30m), with a high number of elements, very narrow beamforming can be accomplished and with Massive MIMO techniques a large number of simultaneous users are able to receive the full spectrum from the same site with little or no mutual interference. The Massive MIMO technique allows, when applicable, to reach a particular user with a high gain, while at the same time causing zero or minimum interference to other users. This can be achieved via dynamic pre-processing of the signals feeding the antenna elements. The effect is that the nulls of the antenna diagram fall on the positions of other unicast users. The broadcast network was assumed to be a single SFN with no significant self-interference, whereas the unicast modelling included interference from other cells of the hexagon network.

It is reported that with 100 users, randomly positioned in the cell, 50% of these would receive more than 1 Gbps and 50% less than this. Assuming a user experience of 100 Mbps one such “1 Gbps user” could in reality be 10 real users via e.g. TDM and with an overbooking factor of 20 (representing the “statistical multiplexing” effect - this figure is typical for commercial networks) the cell could thus serve about  $100 \times 10 \times 20 = 20\,000$  users, each having an experienced 100 Mbps access (when used).

With 100 such cells in the network this could serve about 2 million users with 100 Mbps, assuming users are evenly distributed. One user could e.g. be one household, so the number of actual people served could be significantly larger than this.

This could be achieved while still transmitting broadcast using WiB. Within the SFN (with no interference from adjacent SFNs) the broadcast layer could easily be removed, so should not limit the unicast capacity (but performance may be limited by noise).

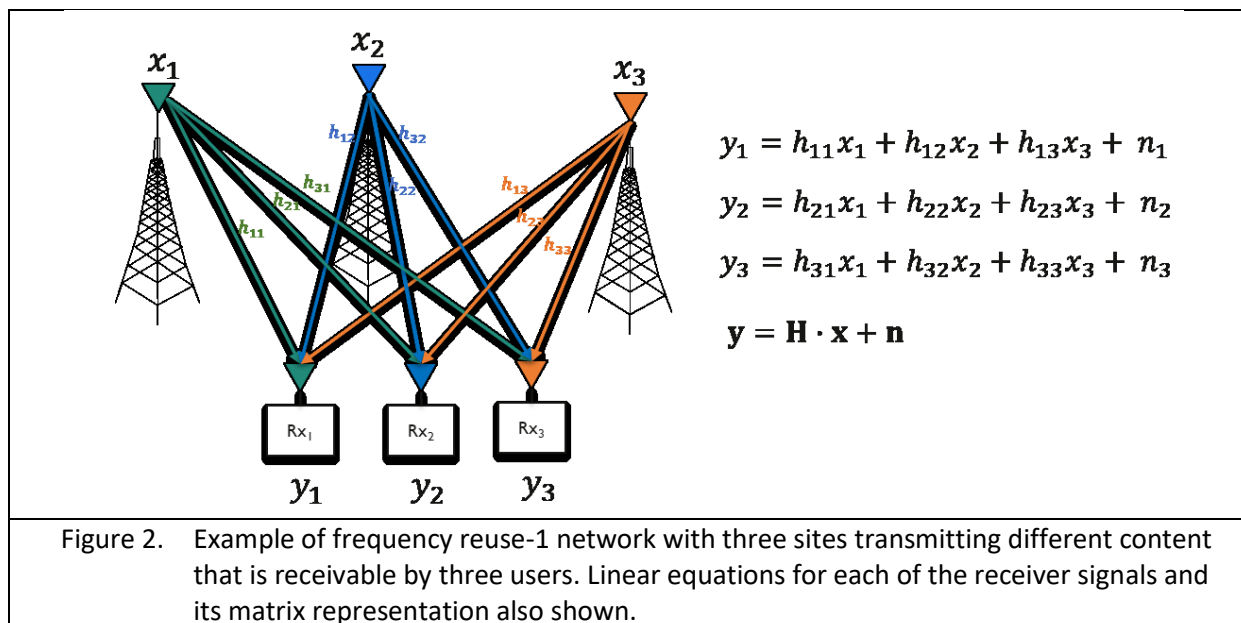
The uplink was not considered in this study, but TM-WiB has noted that the described scheme could either be part of a supplemental downlink, where another bi-directional system would form the anchor, or could be an integral part of such a WiB system, in which case some spectrum (in time or frequency) would need to be allocated for the uplink. It does not seem feasible to share downlink and uplink in LDM, so these probably need to rely on FDM or TDM.

### 3. Physical Layer Model, Theoretical Limits and Receiver Processing Methods

This section describes the underlying physical model which is then used to derive the theoretical limits achievable with WiB, and approaches to processing in the receiver which could be to try to approach these limits.

#### 3.1. Physical layer Models

A user in a frequency reuse-1 network, where the sites transmit different content but in the same frequency (co-channel), can receive its own wanted signal plus additional signals from other sites that act as interferers. An example system model for a frequency reuse-1 network with three single-antenna transmitters and three single-antenna users is illustrated in Figure 2.



At the first user, the discrete complex base-band model for the received signal  $y_1$  can be mathematically expressed<sup>1</sup> at the  $n$ th sample as  $y_1[n] = h_{11}[n]x_1[n] + h_{12}[n]x_2[n] + h_{13}[n]x_3[n] + n_1[n]$ , where  $h_{ij}$  is the channel coefficient between the  $i$ th single-antenna user and the  $j$ th single-antenna transmitter,  $x_j$  is the information symbol of the  $j$ th transmitter, and  $n_i \sim CN(0, \sigma^2)$  is additive circularly symmetric complex Gaussian noise where  $\sigma^2$  is the noise power.

In the general case in a network with  $N_t$  transmitters and  $N_r$  receivers the discrete complex baseband model can be expressed in vector form as  $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$ , where  $\mathbf{y}$  is the  $N_r \times 1$  vector of received symbols,  $\mathbf{x}$  is the  $N_t \times 1$  vector transmitted symbols,  $\mathbf{n} \sim CN(\mathbf{0}, \sigma^2 \mathbf{I})$  is  $N_r \times 1$  additive circularly symmetric complex Gaussian noise and  $\mathbf{H}$  is a  $N_r \times N_t$  matrix with the channel coefficients between the  $i$ th single-antenna user and the  $j$ th single-antenna transmitter denoted as  $h_{ij}$ .

In the networks studied in this report, since the signals  $x_j$  are transmitted from different sites the following power constrain applies  $\sum_j^{N_t} P_j = N_t$ .

The statistics of  $\mathbf{H}$  depend on the propagation environment. In the case that the transmit antennas are sufficiently separated (as it is the case in this report since it considers transmit antennas in different sites), equally polarised and with many scatters the elements of the matrix  $\mathbf{H}$  can be modelled with i.i.d. (independent and identically distributed) zero-mean complex Gaussian components, i.e.  $h_{ij} \sim CN(0,1)$ ,  $i = 1 \dots N_r$  and  $j = 1 \dots N_t$ . Fading components with such characteristics are known as Rayleigh distributed and denoted in the following as  $\mathbf{H}_w$ . This type of modelling is appropriate for environments where there is no direct line-of-sight (NLOS) between the transmitter and receiver, hence are commonly used to model portable and mobile conditions. However, in the case of fixed rooftop reception where there is normally a strong line-of-sight (LOS) the following modelling is more appropriate:  $\mathbf{H} = \sqrt{\frac{K}{1+K}} \bar{\mathbf{H}} + \sqrt{\frac{1}{1+K}} \mathbf{H}_w$ . The term  $\bar{\mathbf{H}}$ , which models the LOS component, is a matrix of size  $N_r \times N_t$  with channel coefficients terms  $\bar{h}_{ij} = \exp i\theta_{ij}$ , where  $\theta_{ij}$  is a fixed random phase uniformly distributed between  $[0, 2\pi)$ . The factor  $K$  describes the power ration between the LOS and NLOS components and assumed in this report to  $K=10$ , unless otherwise stated.

Regarding the channel power, it is defined as the squared Frobenius matrix norm:  $\|\mathbf{H}\|_F^2 = \sum_{i,j}^{N_r, N_t} |h_{ij}|^2 = N_r N_t$  and it is an appropriate constrain in the case of transmit and receive antennas with the same polarisation.

The modelling presented above is general for a network with  $N_t$  transmitters and  $N_r$  receivers. Unless otherwise stated, it is usually assumed that the transmitters are equipped with single transmit antenna<sup>2</sup> and the receivers are also equipped with a single receive antenna. In this report since the performance is calculated for each of the users independently (i.e. there is no joint

<sup>1</sup> In this report it is assumed that the receivers sample the received signals sufficiently fast to fulfil the Nyquist rate signalling criterion and hence the signals can be represented by a discrete baseband model. Also the index  $n$  is omitted for simplicity in the rest of the report.

<sup>2</sup> Here, with the term "antenna" we refer to the combination of RF tuner and antenna aeralis. It is possible that a site has multiple aeralis to form a desired antenna diagram pattern, however from the point of view of the mathematical model this is represented as a single transmit antenna.

decoding across receivers) it is assumed in the rest of the report to calculate the different performance metrics that  $N_r = 1$ .

### 3.2. Theoretical limits

#### 3.2.1. Unconstrained Shannon limits

In order to establish the achievable data rates, it is useful to consider an upper bound. If the upper bound provides a significant benefit, then more realistic limits can be explored to see how close they come to this upper bound.

The most fundamental limit to the available data rate is the Unconstrained Shannon limit [2], which gives the maximum capacity  $C$  achievable between a transmitter and a receiver in a given bandwidth  $B$  for a given received signal power  $P$  and noise power  $N$ . Normally the bandwidth will be taken into account by giving the capacity in bit/s/Hz, in which case the Shannon formula is

$$\frac{C}{B} = \log_2 \left( 1 + \frac{P}{N} \right)$$

In a WiB scenario, in addition to the wanted signal and the thermal noise, we must consider the interfering signals from other transmitters. For a system achieving the Shannon capacity in the presence of Gaussian noise, it is known that the transmitted signals must themselves have a Gaussian distribution of amplitudes. Therefore it is always possible for a receiver to treat the unwanted signals as noise; the sum of these unwanted signals and the thermal noise will also have a Gaussian distribution and the resulting capacity will be given by the same formula, but in which the noise term  $N$  is replaced by the sum of powers of the noise plus the interfering signals  $I_n$ :

$$\frac{C}{B} = \log_2 \left( 1 + \frac{P}{N + \sum I_n} \right)$$

However, better performance can often be achieved by taking into account knowledge about the interfering signals, including the various kinds of joint demapping, joint decoding and interference cancellation which will be discussed in the following sections.

Whatever the receiver does, the capacity obtained from a particular transmitter can never exceed the capacity  $C_{i0}$  of the signal from that transmitter in the presence of noise, ignoring the interfering signals, i.e.

$$\frac{C_{i0}}{B} = \log_2 \left( 1 + \frac{P_i}{N} \right)$$

In such cases, the Shannon limit can be applied to the *total* received power of the signals being jointly processed, to obtain the total *sum capacity* that can be extracted from the two or more signals:

$$C_{sum} = \frac{\sum C_i}{B} = \log_2 \left( 1 + \frac{\sum P_i}{N + \sum I_n} \right)$$

If we define a space in which each axis represents  $C_i$ , the capacity available from one of the transmitters, then, taken together, these limits demarcate a *capacity region* in this space [3]. The simplest case of one wanted signal and one interferer will be considered first.

### 3.2.2. Single interferer case

For the case of two transmitters, the capacity region is a five-sided shape, see figure 3, bounded by the axes, the individual limits  $C_{10}$  and  $C_{20}$  and the diagonal line  $C_1 + C_2 = C_{sum}$  defined by the sum capacity. Within the TM-WiB group, this has been referred to as the *Shannon Pentagon*.

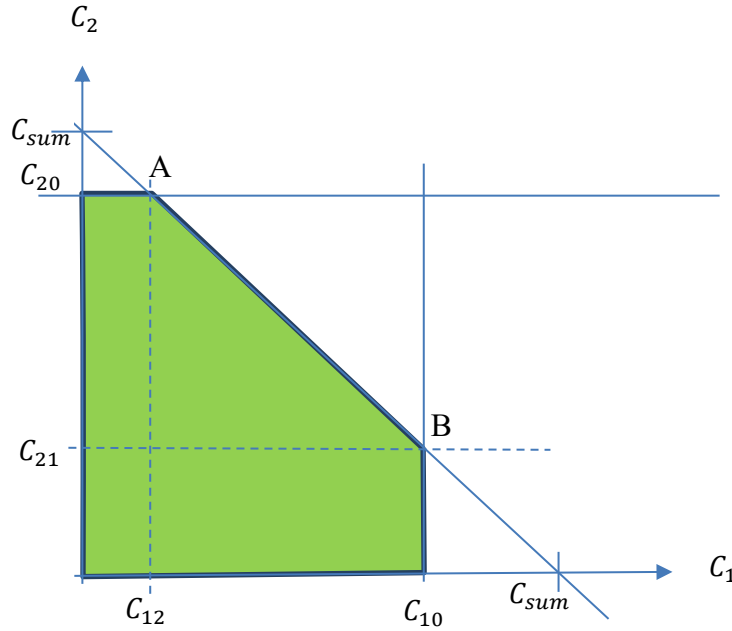


Figure 3. The Shannon pentagon

Also shown in the figure, with dashed lines, are the capacities  $C_{12}$  and  $C_{21}$  from each transmitter treating the signal from the other transmitter as an interferer. By calculating each of the capacities, it can be shown that these lines intersect the capacity region at exactly the corner points A and B. This is not a coincidence, but is a consequence of the Chain Rule for Mutual Information [4]:

$$C_{sum} = I(Y; X_1, X_2)$$

$$C_{21} = I(Y; X_2)$$

$$C_{10} = I(Y; X_1 | X_2)$$

But the chain rule implies that

$$I(Y; X_1, X_2) = I(Y; X_2) + I(Y; X_1 | X_2)$$

$$C_{sum} = C_{21} + C_{10} (= C_{12} + C_{20})$$

Hence the points A( $C_{12}, C_{20}$ ) and B( $C_{10}, C_{21}$ ) both lie on the sum capacity line  $C_1 + C_2 = C_{sum}$ .

The corner points represent the two possible sequences for *successive interference cancellation*. Point A corresponds to:

- decoding signal 1 treating signal 2 as noise, achieving  $C_{12}$ , then

- subtracting signal 1 (which can be perfectly reconstructed from the error-free decoded signal), and
- decoding signal 2, now in the presence only of the thermal noise, hence achieving  $C_{20}$ .

Point B corresponds to the reverse process with signals 1 and 2 exchanged. Clearly, if the individual Shannon capacities can be achieved, then the combinations A and B can also be achieved.

Reference [3] continues at this point to discuss the points on the diagonal between A and B, explaining that these points can also be achieved by *time sharing*: time-division multiplexing between a scheme that achieves point A and one that achieves point B. Although the phrase “time sharing” is used, more generally the result can be achieved by sharing *orthogonal resource units* between the two schemes. An orthogonal resource unit is the opportunity to send one complex number from transmitter to receiver without interference from any other orthogonal resource units: for example, an OFDM cell, or a symbol in a single-carrier system.

However, it should be noted that the schemes that achieve A and B require different capacities from each of the transmitters, which in practical terms implies different code rates and/or constellations. Furthermore, the ratio in which the resource units are shared between the two schemes depends on the desired position on the line. In the kind of Multiple Access system discussed in the literature, there is usually assumed to be only one receiver, usually a cellular base station, as well as a return path from this to the transmitters, usually the User Equipment (UE) or handsets. This return path can be used to control the code-rates for the two schemes and the sharing ratio between them, allowing the desired operating point on the pentagon to be achieved. In addition, the bit-rate can be adjusted according to the conditions.

In a broadcast scenario as considered for WiB, none of these assumptions is valid; instead:

- There is no back-channel to allow adjustment to suit particular receiving conditions
- There will be a large number of receivers at different locations, each receiving a different combination of signal powers from the two transmitters
- The transmitters will be carrying a broadcast service at a particular bit-rate and this same bit-rate will need to be transmitted from all the transmitters in a network. There is no scope for adjusting the bit-rates to match the conditions.

As a result, the capacity region concept has had to be extended to cover the broadcast case.

The first key development is to consider whether and how a scheme can achieve points along the sloping portion AB of the boundary without the ability to use orthogonal-resource sharing. This will be discussed in the next subsection (3.2.3).

Assuming for the moment that this can be achieved, the other development is to introduce the assumption of equal capacity: each transmitter in the network will carry information at a particular data-rate, this data rate will be the same for all transmitters. According to the local conditions, a given receiver will be able to decode the signal either from one or more of the transmitters in the network, or from none of them. These are very familiar assumptions in broadcast network planning, but need to be borne in mind when transferring ideas from cellular networks.

The equal-capacity assumption can be added to the rate region chart by introducing the line  $C_1 = C_2$ , a diagonal line at 45° perpendicular to the sum-capacity limit. This suggests that the best capacity that can be achieved under the equal rate assumption is determined by the point at which the equal capacity line crosses the boundary of the rate region. There are three cases, shown in figure 4. In each case, the equal capacity line is shown in red.

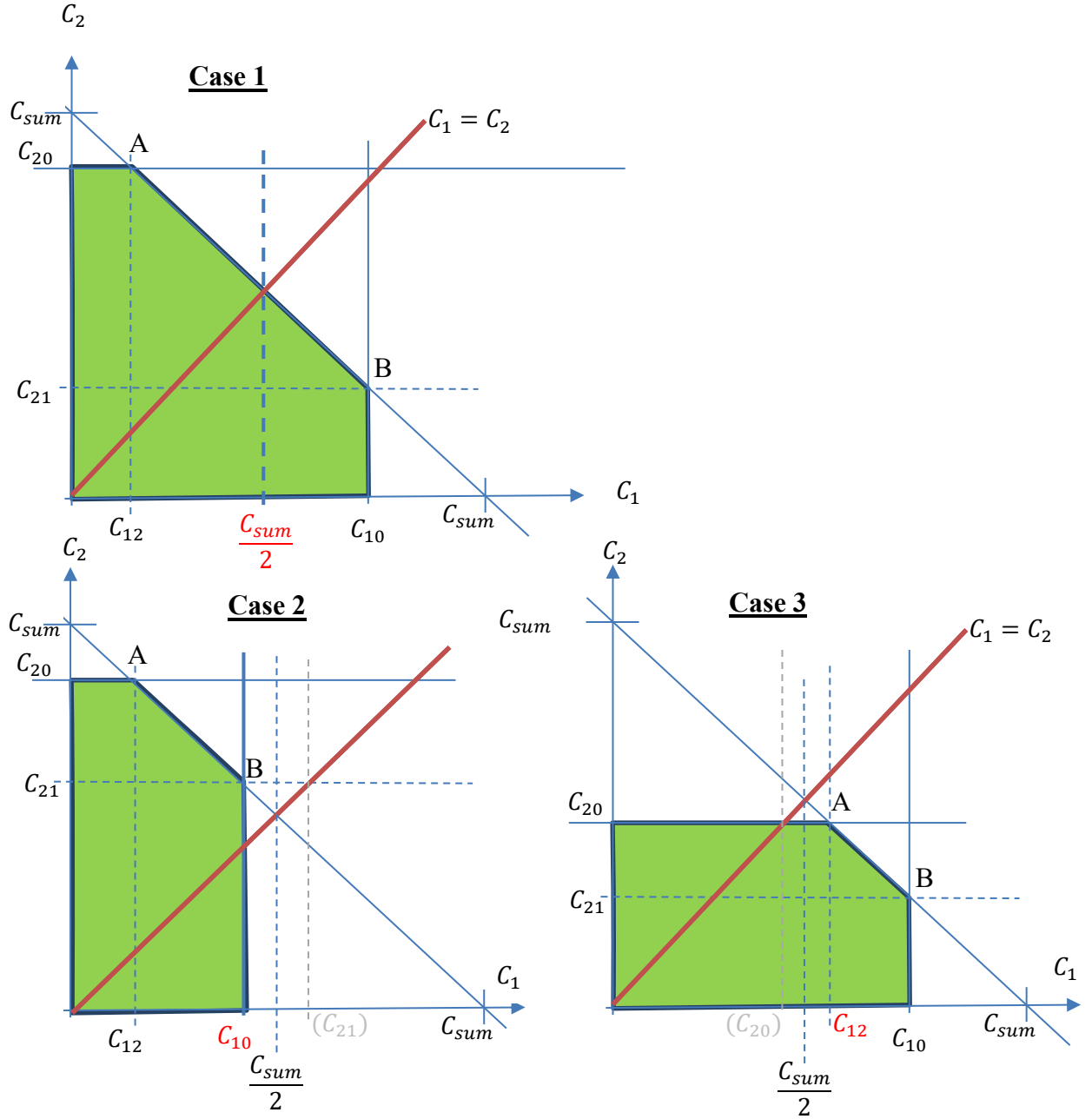


Figure 4. The three reception scenarios for the Shannon pentagon

- Case 1: The equal-capacity line meets the diagonal sum-capacity limit between A and B: this implies  $C_1 = C_2 = \frac{C_{sum}}{2}$ .



- Case 2: If the line instead crosses the vertical portion below B, then signal 2 can be decoded first, subtracted, and then signal 1 decoded, giving capacity  $C_1 = C_{10}$ . Note that the available capacity for signal 2, treating signal 1 as noise, is  $C_2 = C_{21}$ , and that  $C_{21} > C_{10}$  (see the dashed grey line for confirmation). In practice, since both transmitters would have the same bit-rate, signal 2 would have excess C/N in this situation.
- Case 3: The line crosses the horizontal portion of the boundary, to the left of A, then, apparently, the capacity is limited by the power of signal 2, to  $C_1 = C_2 = C_{20}$ . However, since signal 1 is the wanted signal (by definition), it is not necessary to extract any information from signal 2; instead it can be treated as noise, giving a capacity  $C_1 = C_{12}$ . Since  $C_{12} > C_{20}$  in this case, and equal rates are transmitted from both transmitters, signal 2 would have insufficient C/N to be decoded.

Hence, the available rate is  $\frac{C_{sum}}{2}$ ,  $C_{10}$ , or  $C_{12}$  depending on which of the three segments of the boundary the  $C_1 = C_2$  line crosses, but the capacity is not necessarily given by the value of  $C_1$  at this intersection point.

An alternative way to derive the capacity is to say that the joint capacity can be shared, giving  $\frac{C_{sum}}{2}$ , but not if this exceeds the capacity  $C_{10}$ ; and it is always possible to treat signal 2 as noise, achieving  $C_{12}$ , so the capacity available is the better of these two options, i.e.

$$C = \max\left(\min\left(\frac{C_{sum}}{2}, C_{10}\right), C_{12}\right)$$

Comparison of the “winner” in each of the three cases should confirm that the formula is correct.

### 3.2.3. Achievability of the sum capacity

In the discussion above, it was assumed that the sum capacity  $C_{sum} = \log_2\left(1 + \frac{P_1 + P_2}{P_N}\right)$  could be achieved. Recall that in the cellular, unicast case, the argument is usually made that any point on the sloping part of the rate region boundary can be achieved using resource sharing between the corner points A and B, which represent the two possible orders of successive interference cancellation (“Hard-SIC”).

As discussed, such resource sharing needs to be adaptive: varying the proportion of resources allocated to each scheme depending on the received power from the two transmitters, and this is not possible in the broadcast case because the proportion and code-rates required will vary between the many receivers in the reception area. Is it therefore reasonable to assume that the capacity  $\frac{C_{sum}}{2}$  per transmitter can be achieved, even in theory, for all the receivers simultaneously? Furthermore, would such a code also perform at capacity for the other cases?

The unconstrained Shannon Capacity formula can be derived [3] based on the assumption that each transmitter transmits very long sequences, in which the samples of each codeword are randomly chosen from a Gaussian distribution. The codewords are therefore represented by points in  $L$ -dimensional space taken from a multivariate Gaussian distribution, where  $L$  is the length of the codeword. As  $L \rightarrow \infty$ , the probability of error can be made arbitrarily low provided the capacity is less than that given by the Shannon formula.

In our broadcast case, suppose that any given transmitter transmits long codewords of this form. Suppose that the number of codewords has been chosen so as to achieve the required spectral efficiency in the no-interference case. We know from the argument above that such a code will be decodable without errors provided the S/N is high enough for the capacity formula to be satisfied.

In the cases where the interferer is treated as noise, such that the capacity is  $C_{12}$ , the wanted signal 1 needs to be decoded in the presence of the combined signal formed by signal 2 plus the noise; since both signal 2 and the noise have Gaussian distributions, the combined signal is also Gaussian and hence the capacity is no different to the case where there is only noise of the same total power.

In the case where signal 2 needs to be first decoded and then subtracted before decoding signal 1 to achieve  $C_{10}$ , the situation is reversed with respect to decoding signal 2, i.e. the combination of signal 1 and the noise forms a new Gaussian-distributed signal which will result in the same capacity as if there was only noise present of the same total power. Once signal 2 has been subtracted, there is only signal 1 and the noise left, hence the capacity  $C_{10}$  can be achieved.

In the case where signals 1 and 2 are to be jointly decoded to achieve the sum capacity  $C_{sum}$ , the “wanted” signal is in fact the signal formed by adding together signals 1 and 2. Since each is individually Gaussian-distributed, the combined signal is also Gaussian distributed with the combined power of the two signals; in other words the combined signal represents a new long Gaussian code. The same argument can be applied to deduce that this can be decoded error-free provided that the total bit-rate meets the Shannon limit for the total power and the noise level.

The argument in annex B.5.2 of [3] states that the Shannon limit is achieved with very high probability for a very long code generated at random from the Gaussian distribution. This therefore implies that a combination of two such codes would also achieve the sum capacity limit with very high probability. However, over a coverage area and over time, many different combinations of the two transmitted codes will occur. For a given transmitted code there may be some pathological combinations which lead to an atypically bad combined code. A more rigorous analysis would be needed to establish how likely such a combination is to occur.

This subsection has presented the outline of an argument that shows that a fixed code, designed to achieve the Shannon limit for an individual signal, will also achieve the sum capacity limit when combined with another similar (or identical) code.

In practice, Gaussian codes like this are impractical: because the codewords are chosen at random, the only approach to decoding them would be a brute-force search through all the possible codewords. Attempting to decode the *sum* of two codewords in this way would multiply the number of combinations astronomically.

Practical codes can provide capacities that come close to the Shannon limit, but in order to achieve the sum capacity, the codes would need to permit decoding under a wide range of relative signal levels. Possible practical approaches are proposed and analysed in section 3.3.

#### **3.2.4. Capacity contours**

A “Shannon pentagon” plot shows only one particular combination of S/N and S/I conditions, so cannot show how the available capacity changes with changing conditions. Figure 5 shows contours of capacity as a function of S/N and S/I. Each contour comprises three segments corresponding to

the three cases in figure 4. The regions corresponding to the three cases are labelled. At very high  $S/I$ , the interferer is almost irrelevant and can be treated as part of the noise (case 3). At very poor (i.e. negative)  $S/I$ , the interferer is much stronger than the wanted signal and can be decoded and subtracted, leaving only the wanted signal and the noise (case 2). Joint decoding to obtain the sum capacity (case 1) is appropriate at intermediate  $S/I$  values around 0dB. Here the wanted and interfering signals are of similar levels: the interferer cannot be ignored but nor can it be decoded and cancelled.

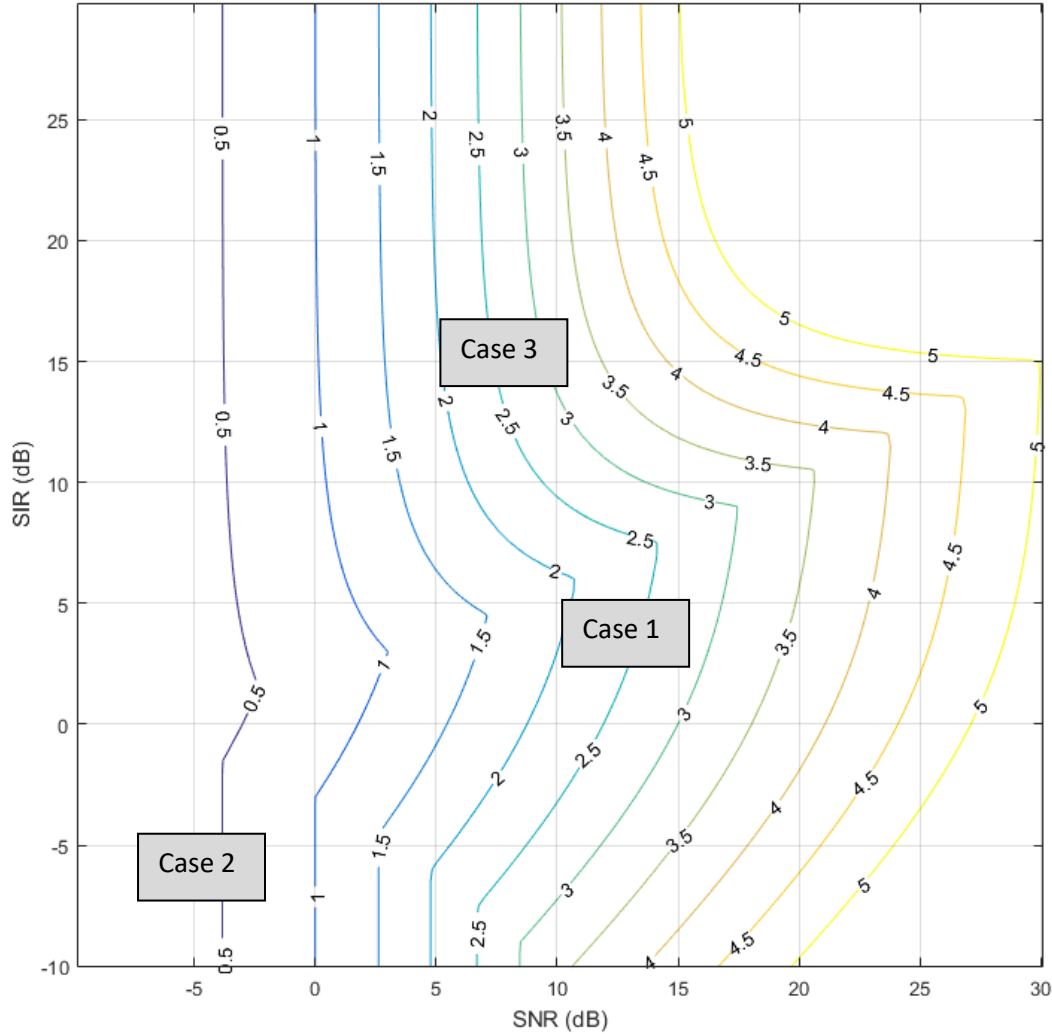


Figure 5. Capacity contours for the Shannon pentagon

### 3.2.5. Two-interferer case

The analysis that led to the “Shannon pentagon” in section 3.2.2 can be extended to the case of a wanted signal interfered with by two other transmitted signals. The rate region becomes a region of 3-dimensional space defined by the capacities of the three signals. The region is bounded by seven planes. There are three planes perpendicular to the axes, representing the maximum capacity available given the power received from each transmitter individually. There is a diagonal plane

representing the constraint that the sum capacity across all three signals is limited by the total received power. In addition, there are three planes each corresponding to the pairwise sum capacity of two of the three signals. The resulting region, shown in figure 6, has been referred to in the working group as the “Shannon Diamond” in reference to its supposed similarity to a cut diamond.

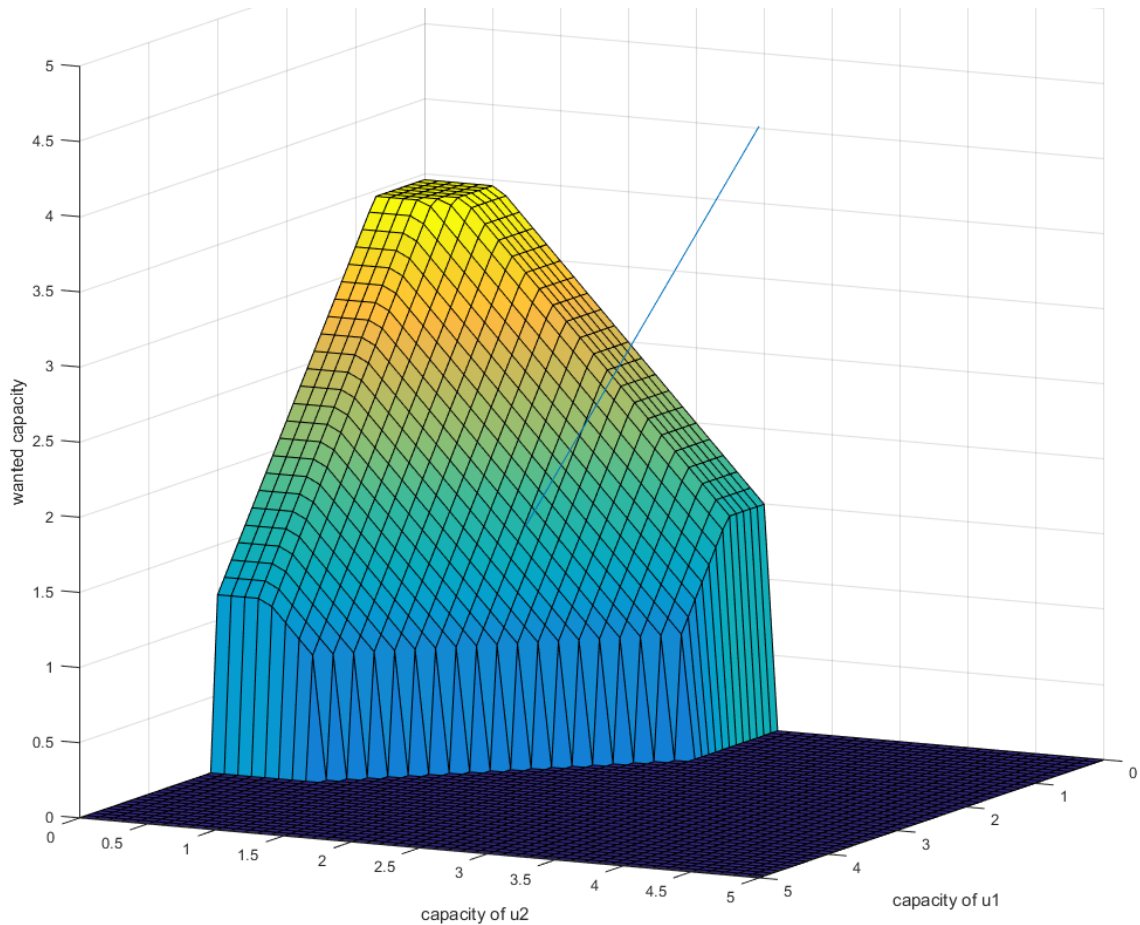


Figure 6. The Shannon diamond

This can be analysed in a similar way to a single interferer. There are many more options and therefore the formula becomes difficult to write down succinctly. Nevertheless, it has the same general form: a maximum taken over a series of minimums.

It might be thought that the “winning” capacity would be determined by which facet of the diamond the line of equal capacity ( $C_1 = C_2 = C_3$ ) crosses, in the same way that the capacity in the single-interferer case is determined by the segment of the boundary the equal capacity line crosses. This is partly true, but for some facets there is more than one case, so in fact it turns out that there are nine different rates. Furthermore, there are 11 different decoding sequences, but three of these give the same rate. This is explained in detail in the Annex.

In principle the calculation could be extended to three or more interferers, but for most of the networks considered, this was not expected to give a significant further improvement in capacity compared to treating all the other interferers as noise.

### 3.2.6. BICM

Given the system model with a transmit signal  $\mathbf{x}$  and a received signal  $\mathbf{y}$  through a channel  $\mathbf{H}$  with the relationship  $\mathbf{y}=\mathbf{H}\mathbf{x}+\mathbf{n}$ , bit-interleaved coded modulation (BICM) maximum achievable rate assuming an ideal infinite length interleaver is given by [5]:

$$C_{\chi}^{\text{bicm}} \triangleq \sum_{j=1}^m E_{\mathbf{x}, \mathbf{y}, \mathbf{H}} \left\{ \log_2 \frac{\sum_{\mathbf{x}' \in \chi_j^{c_j}} f(\mathbf{y}|\mathbf{x}', \mathbf{H})}{\frac{1}{2} \sum_{\mathbf{x}' \in \chi} f(\mathbf{y}|\mathbf{x}', \mathbf{H})} \right\} \quad (3.0)$$

where the conditional pdf  $f(\mathbf{y}|\mathbf{x}, \mathbf{H})$  is given by [5]

$$f(\mathbf{y}|\mathbf{x}, \mathbf{H}) = \frac{1}{(\pi\sigma^2)^{N_r}} \exp\left(-\frac{\|\mathbf{y}-\mathbf{H}\mathbf{x}\|^2}{\sigma^2}\right), \quad (3.1)$$

$\chi$  is the set of possible (constellation) signals of the transmit vector  $\mathbf{x}$ , the expectation operator  $E$  is over all possible transmit, receive and channel signals  $\mathbf{x}$ ,  $\mathbf{y}$ ,  $\mathbf{H}$ , and  $m$  is the number of raw bits per channel use. In particular  $m = m_1 + m_2 + \dots + m_{N_t}$  where  $m_1, m_2, \dots, m_{N_t}$  are the number of bits per constellation symbol transmitted at each transmitter site. In (3.0) the term  $\chi_j^{c_j}$  denotes the set of transmit vectors which have the  $j$ th bit in the label of  $\mathbf{x}$  the value  $[0, 1]$ . In this report the mutual information is measured as described in annex A of [5].

### 3.3. Receiver approaches

#### 3.3.1. Soft-In Soft-Out MAP demodulator

The optimum demodulator maximises the a-posteriori probabilities (MAP) of transmitted code bits and minimises the probability of error. It can be expressed in the form of Log-Likelihood Ratios (LLRs) by the following expression [6]:

$\Lambda_l \triangleq \log \frac{p(c_l = 1 \mathbf{y}, \mathbf{H})}{p(c_l = 0 \mathbf{y}, \mathbf{H})} = \log \frac{\sum_{\mathbf{x} \in \chi_l^1} p(\mathbf{y} \mathbf{x}, \mathbf{H})P(\mathbf{x} = \mathbf{s})}{\sum_{\mathbf{x} \in \chi_l^0} p(\mathbf{y} \mathbf{x}, \mathbf{H})P(\mathbf{x} = \mathbf{s})}$	(3.2)
--	-------

where  $p(c_l = 1|\mathbf{y}, \mathbf{H})$  is the probability mass function of the transmitted coded bits conditioned to the received vector  $\mathbf{y}$  and the channel matrix  $\mathbf{H}$ .  $\chi_l^1$  and  $\chi_l^0$  are the set of constellation symbols with the corresponding bit label  $c_l$  to 1 and 0, respectively, and the conditional Probability Density Function (pdf)  $p(\mathbf{y}|\mathbf{x}, \mathbf{H})$  is given by the expression in (3.1):

The transmitted vector probability  $P(\mathbf{x} = \mathbf{s})$  can be expressed as [7, 5]:

$P(\mathbf{x} = \mathbf{s}) = \prod_{l=1}^m P\{c_l = b_l\} = \prod_{l=1}^m \frac{\exp(-b_l L_a(c_l))}{1 + \exp(-L_a(c_l))}$	(3.3)
---	-------

where  $b_l \in \{0,1\}$  is the bit label of  $\mathbf{s}$  and  $L_a(c_l)$  is the a priori LLR for  $c_l$  which can be provided by the channel decoder and  $m$  is the number of bits of the combined transmitted vector across the jointly demodulated transmitters

Using (3.2), (3.1) and (3.3) and some expression manipulations [7], (3.2) is expressed as:

$$\Lambda_l = \log \frac{\sum_{\mathbf{x} \in \mathcal{X}_l^1} \exp \left( -\frac{1}{\sigma^2} \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2 + \sum_j b_j L_a(c_j) \right)}{\sum_{\mathbf{x} \in \mathcal{X}_l^0} \exp \left( -\frac{1}{\sigma^2} \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2 + \sum_j b_j L_a(c_j) \right)} \quad (3.4)$$

where the summation of the a-priori LLRs  $L_a$  spans all the label bits that are equal to 1.

Despite the optimal error rate performance of the MAP demodulator, for each demodulator execution (assuming all sites transmit with the same constellation order) the complexity order is  $O(|A|^{N_t})$  where  $|A|$  is the cardinality of the constellation  $A$  (e.g.  $|A| = 4$  for QPSK). That is, complexity increases exponentially with the number of jointly demodulated transmitters.

To reduce the computational complexity of the MAP demapper the max-log approximation  $\log(\sum_i \exp(x_i)) \approx \max_i \{x_i\}$  replaces the computation of logarithmic and exponential functions to a minimum distance problem more suitable for hardware implementation with reduced performance loss. Applying the max-log approximation to (3.2) and similar expression manipulations to those in (3.4) the approximate LLRs have the form [7]:

$$\begin{aligned} \widetilde{\Lambda}_l = \min_{\mathbf{x} \in \mathcal{X}_l^0} \left( \frac{1}{\sigma^2} \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2 + \sum_j b_j L_a(c_j) \right) \\ - \min_{\mathbf{x} \in \mathcal{X}_l^1} \left( \frac{1}{\sigma^2} \|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2 + \sum_j b_j L_a(c_j) \right) \end{aligned} \quad (3.5)$$

### 3.3.2. Joint De-mapping

The demodulator that performs joint de-mapping of the constellation symbols transmitted across the  $N_t$  sites conveying different content as in (3.4) but without a-priori information fed from the channel decoder (i.e.  $L_a$  is a zero vector) becomes a maximum likelihood demodulator. In the rest of the report this type of demodulator will be called “Joint De-mapping”.

### 3.3.3. Gaussian de-mapping

An alternative approach to the demapping strategies of MAP and Joint De-mapping is to assume that only one site (or group of sites carrying the same content in a SFN cluster) is demodulated and consider the rest of  $N_t - 1$  sites as part of the receiver Gaussian noise.

For this demodulator expression (3.4) takes the values  $N_t = 1$ , no a-priori information is fed from the channel decoder (i.e.  $L_a$  is a zero vector) and the noise variance is changed to the following expression:

$$\tilde{\sigma}^2 = \sigma^2 + \sum_{j=2}^{N_t} P_j E \{ |h_{1j}^r|^2 \} \quad (3.6)$$

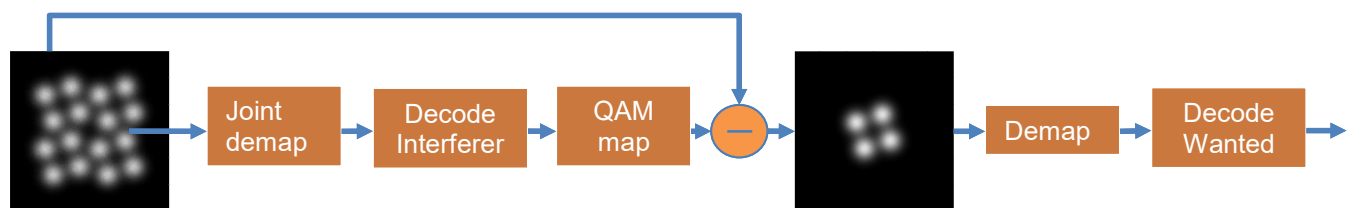
where  $P_j$  is the transmit signal power at the  $j$ th site and  $|h_{1j}^r|^2$  is the channel power at the receiver position from  $j$ th transmitter.

### 3.3.4. Successive Interference Cancellation

Joint De-mapping (see section 3.3.2) takes into account only the *constellation* being used by the interferer. Better performance can be obtained by also taking into account the *coding* of the interferer. The simplest way of doing this is known as Successive Interference Cancellation (“SIC”): the strongest signal is decoded and the result is used in demapping and decoding the successively weaker signals. The most basic form is referred to in this document as “Hard-SIC”, and consists of the following steps:

- Perform Joint Demapping of the received signal
- Attempt to decode the strongest signal
- Re-encode and remap the strongest signal
- Subtract the remapped signal from the received signal
- Perform joint demapping of the remaining signals
- Attempt to decode the next strongest signal
- Continue until the desired signal has been decoded

The process is illustrated in the block diagram below.



The first step is simply Joint Demapping as discussed in section 3.3.2.

Once the strongest signal has been decoded, the subsequent demapping stages proceed according to equation 3.2, but in which the prior probabilities  $P\{c_l = b_l\}$  of equation 3.3 take only the values 1 or 0 for the bits belonging to the signal(s) that have already been decoded. That is, the bits already decoded are presumed to be known with certainty. As a result,  $P(\mathbf{x} = \mathbf{s}) = 0$  for some of the candidate constellation points  $\mathbf{x}$ , and these vanish from the marginalisation. For each previously decoded bit, half of the candidate points disappear, leaving in effect a lower-order constellation carrying only the as-yet unknown bits. This is exactly the constellation that would be received if the stronger signal were absent, except that it is centred on the (now known) constellation point from the stronger signal. Hence the process of subtraction in the above diagram is equivalent to the demapping process described.

Provided the conditions allow the strongest signal to be decoded without errors, the assumption of certainty ( $\Pr(c_l = b_l) \in \{0,1\}$ ) will give optimum results in decoding the weaker signal(s).

However, any errors in the earlier decoding stages are likely to cause severe damage to the subsequent decoding steps, essentially because incorrect information with high confidence is presented to the demapper and decoder. A natural extension is to use *soft* output from the first decoding stage to provide the  $\Pr(c_l = b_l)$  values used in the demapper (equation 3.3). In practice

this is likely to mean using soft LLR output values  $L_a(c_j)$  in the formulation of equation 3.4. This process is referred to as “Soft-SIC”. Soft-SIC is not dealt with in detail in this document; instead it can be considered as a special case of JIDD (see section 3.3.6) with a single iteration for each signal.

Hard-SIC is amenable to convenient capacity analysis using the BICM limits without the need to make any assumptions about the particular codes used. The following reasoning can be applied:

- If the wanted signal is the strongest, then no cancellation will be performed. The capacity will be the same as for Joint Demapping, since the steps performed are identical.
- If the wanted signal is the second-strongest, then the receiver will first perform Joint Demapping and attempt to decode the strongest signal.
- This will be successful provided the capacity of strongest signal, under joint demapping, in the presence of all the weaker signals plus the noise, is not exceeded
- The capacity of the wanted signal will then be given by the Joint Demapping capacity in the presence only of the weaker signals and the noise
- Since the strongest signal (the interferer) is assumed to be part of the same broadcast network as the wanted signal, it must in practice convey the same bit-rate as the wanted signal. Hence the capacity available assuming hard-SIC is the lesser of these two capacities.

The resulting capacity (for one wanted signal and one interferer) is therefore given by

$$C_{HardSIC} = \max(C_{wi}, \min(C_w, C_{iw}))$$

Where  $C_{wi}$  is the capacity of the wanted in the presence of the interferer and noise,  $C_{iw}$  is the capacity of the interferer in the presence of the wanted signal, and  $C_w$  is the capacity of the wanted signal in the presence of noise only.

These can be expressed in terms of the Joint Demapping capacity  $C_{JD}(SNR, SIR)$  at a given SNR and SIR (in dB) as follows:

$$C_{wi} = C_{JD}(SNR, SIR)$$

$$C_{iw} = C_{JD}(CNR - SIR, -SIR)$$

$$C_w = C_{JD}(SIR, \infty)$$

Note that  $C_{wi}$  is always available, but in practice it will only be selected by the “max” in cases where the wanted signal is stronger than the interferer ( $S/I > 0$  dB).

### 3.3.5. Capacity contours for Joint Demapping and Hard-SIC

Figure 7 shows the contours of capacity for Joint Demapping (solid lines) and Hard-SIC (dashed lines).

Looking first at the JD contours (solid), we see the same general behaviour as for the Shannon Pentagon (section 3.2.2): at high  $S/I$ , the interference is negligible and the capacity asymptotes to the value limited by the  $S/N$ ; at large negative  $S/I$ , the interferer is so much stronger than the wanted signal that the “mini constellations” are well separated and there is no danger of confusion, so again the capacity asymptotes to the noise-only value; when the two signals are of similar levels, the mini-constellations overlap and the capacity is reduced, or, equivalently, less noise can be tolerated for a given capacity.



Looking now at the dashed contours for Hard-SIC: for positive  $S/I$ , the contours are identical, since in this region joint demapping is the best strategy. When the interferer is a few dB stronger than the wanted signal, it can be decoded error-free and subtracted, leaving only the wanted signal and noise: this leads to the vertical portions of the contours corresponding to the capacity in the presence of noise only. These vertical portions are the asymptotes of JD as the SIR gets very large or very small, but for Hard-SIC they can be achieved at modest a negative  $S/I$ .

At intermediate  $S/I$  values, the capacity is limited by the capacity that can be extracted from the *interferer* in the presence of the wanted signal in the first stage of the Hard-SIC process. If this could be decoded, in principle more capacity could be obtained from the wanted signal, but the broadcast network assumption requires the same bit-rate on both, and this higher bit-rate on the interferer would exceed the capacity available and result in errored reception.

The pale green shaded region shows the range of  $(S/I, S/N)$  combinations for which Hard-SIC outperforms Joint Demapping at an arbitrarily chosen capacity of 1.2bit/s/Hz.

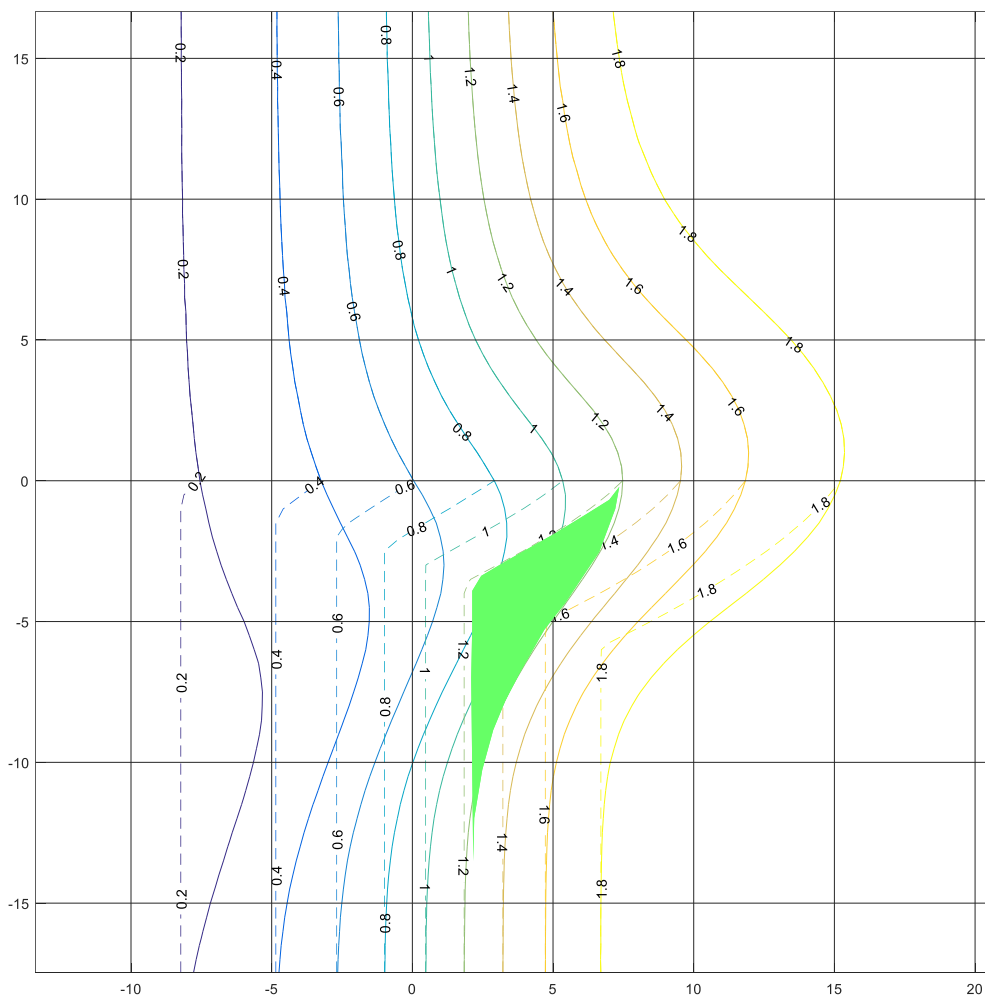


Figure 7. Capacity contours for Joint De-mapping and Hard-SIC, highlighting the beneficial region for Hard-SIC

### 3.3.6. Joint Iterative Demapping & Decoding (JIDD)

Superposition modulation as a means to share a resource medium between users in a non-orthogonal manner has long been known for its ability to exceed the capacity of orthogonal access schemes, e.g., time-division and frequency-division multiplexing [8].

We consider the WiB reuse-1 system setup as representative of superposition modulation and accordingly model the  $k$ -th received cell as

$$r[k] = h_1[k]x_1[k] + h_2[k]x_2[k] + n[k].$$

The transmitted signals are denoted as  $x_1[k] \in A_1$  and  $x_2[k] \in A_2$ . They are drawn from QAM-alphabets  $A_1$  and  $A_2$ . The extension of this model to more than two transmitter sites is considered straightforward and omitted for the sake of clarity. We assume that the receiver has access to channel state information ( $h_1[k]$  and  $h_2[k]$ ) through channel estimation. Noise is accounted for by the AWGN term  $n[k]$  with power  $\sigma^2$ .

It is assumed that the transmitted signals are output by BICM-blocks (see Figure 8). A BICM-block represents a pragmatic approach to Coded Modulation and comprises a binary FEC-code (here, an LDPC-code), bit-interleaver, and a mapping unit which maps groups of bits to QAM-symbols. It is also assumed that FEC-blocks from different transmitters are aligned in such a way that first and last cell of a FEC-block from a first transmitter coincide with first and last cell of a FEC-block from a second transmitter.

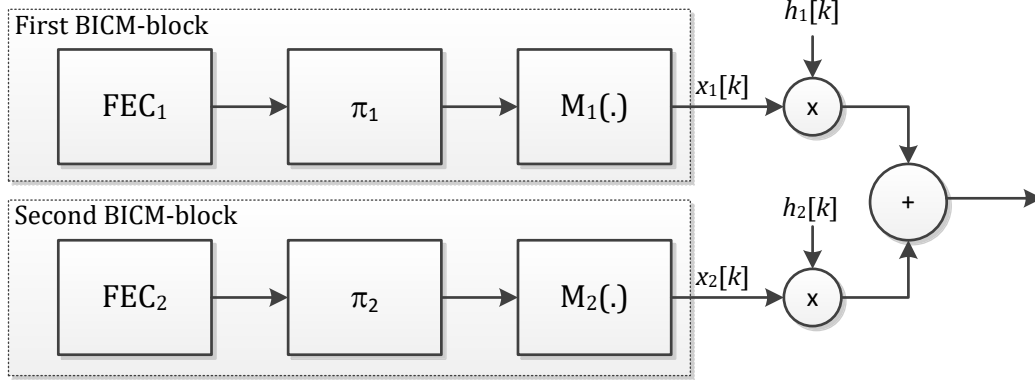


Figure 8: Simplified transmitter model excluding common building blocks (OFDM, interleaving stages)

#### JIDD-Receiver Architecture

The Joint Iterative Demapper and Decoder (JIDD) which is matched to the transmitter structure described above is shown in Figure 9. Its building blocks will be detailed in the following subsections. Joint Iterative Demapping and Decoding is an application of the Turbo Principle, which since the end of the 1990s has been widely recognized as a general principle to achieve near capacity performance of communication systems with reasonable complexity [9]. In this section, we consider JIDD for the demodulation of WiB-signals.

In general, soft information is well-known to yield a considerable SNR gain over hard decision data. Moreover, the iterative exchange of extrinsic soft-information between constituent decoding blocks is the decisive reason for the excellent performance of any turbo scheme. It is also the central idea underlying the JIDD receiver.

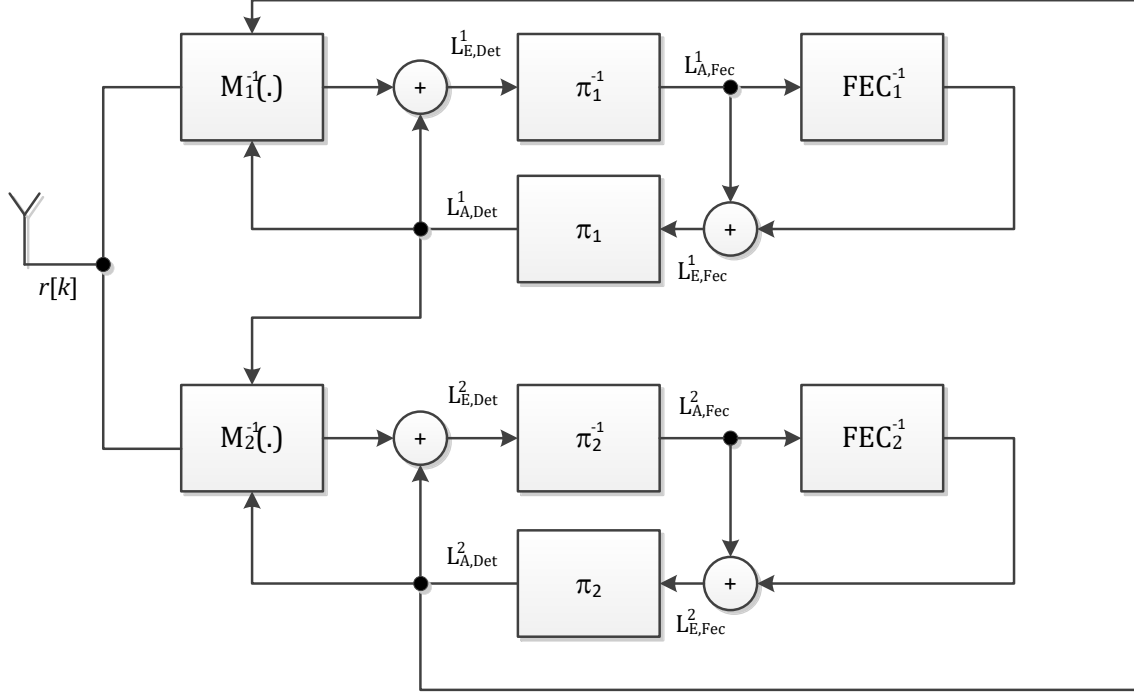


Figure 9. JIDD receiver for two transmitters

### Demapping

JIDD can be viewed as a further development of Gaussian demapping (section 3.3.3) and in particular Joint Demapping (section 3.3.2) in that it also exploits iteratively soft-information from the FEC-decoding stages. The demapping blocks are denoted as  $M_1^{-1}(\cdot)$  and  $M_2^{-1}(\cdot)$ . Based on the received cells, channel state information, the symbol alphabets and a-priori information obtained from FEC-coding, the demappers perform suitable marginalization of the probability density function of the received signal to obtain an L-value which serves as a soft-estimate for the m-th codebit carried by a cell from either the first or the second transmitter:

$$L_{E,Det}^1(m) = \frac{\sum_{x_1 \in A_1^1(m)} \sum_{x_2 \in A_2} \exp\left(-\frac{|r - h_1 x_1 - h_2 x_2|^2}{\sigma^2} - \sum_{i=0}^{ld M_1-1} \mu_i^{-1}(x_1) \cdot L_{A,Det}^1[i] - \sum_{j=0}^{ld M_2-1} \mu_j^{-1}(x_2) \cdot L_{A,Det}^2[j]\right)}{\sum_{x_1 \in A_1^0(m)} \sum_{x_2 \in A_2} \exp\left(-\frac{|r - h_1 x_1 - h_2 x_2|^2}{\sigma^2} - \sum_{i=0}^{ld M_1-1} \mu_i^{-1}(x_1) \cdot L_{A,Det}^1[i] - \sum_{j=0}^{ld M_2-1} \mu_j^{-1}(x_2) \cdot L_{A,Det}^2[j]\right)} - L_{A,Det}^1[m]$$

The marginalization for the first transmit signal is carried out such that the numerator is averaged over all symbols of the second transmitter and over all symbols of the first transmitter which carry the 0-bit as their m-th bit label, signified by the partial symbol alphabet  $A_1^0(m)$ . The denominator is

averaged over all symbols of the second transmitter and over all symbols of the first transmitter which carry the 1-bit as their  $m$ -th bit label, signified by the partial symbol alphabet  $A_1^0(m)$ . Moreover, numerator and denominator consist each of three terms, the first term being the Euclidean distance between the cell hypotheses and the received cell, the second and third terms being the a-priori probabilities for the codebits translated to L-values. Denoted as a convenience function is  $\mu_i^{-1}(x)$  which is an inverse mapping function. For a complex-valued cell  $x$  it returns the  $i$ -th address bit. For the second demapper, the approach is similar with the only difference being that marginalization is performed across the second symbol alphabet  $A_2$ .

$$L_{E,Det}^2(m) = \frac{\sum_{x_1 \in A_1} \sum_{x_2 \in A_2^1(m)} \exp \left( -\frac{|r - h_1 x_1 - h_2 x_2|^2}{\sigma^2} - \sum_{i=0}^{ld M_1 - 1} \mu_i^{-1}(x_1) \cdot L_{A,Det}^1[i] - \sum_{j=0}^{ld M_2 - 1} \mu_j^{-1}(x_2) \cdot L_{A,Det}^2[j] \right)}{\sum_{x_1 \in A_1} \sum_{x_2 \in A_2^0(m)} \exp \left( -\frac{|r - h_1 x_1 - h_2 x_2|^2}{\sigma^2} - \sum_{i=0}^{ld M_1 - 1} \mu_i^{-1}(x_1) \cdot L_{A,Det}^1[i] - \sum_{j=0}^{ld M_2 - 1} \mu_j^{-1}(x_2) \cdot L_{A,Det}^2[j] \right)} - L_{A,Det}^2[m]$$

### LDPC codes

Since their discovery in the 1960s by R. Gallager, LDPC codes (Low-Density Parity Check Codes) have found their application in all second-generation DVB-standards and the recent ATSC 3.0 standard due to their near-capacity achieving performance. They are binary linear block-codes and they are typically defined either via a sparsely populated parity check matrix (PCM) or equivalently a bipartite factor graph. An LDPC code is said to be regular if its row and column weights are constant, whereas it is considered irregular if its row or column weights are non-constant. Irregular LDPC codes are considered to provide higher performance, which is the reason for choosing them in second-generation applications. These codes exhibit additional quasi-cyclic structures and a repeat-accumulate parity part which render them easily encodable and accommodate parallel decoding. Furthermore, it is a convention to call the columns of the PCM variable nodes and its rows check-nodes. A codeword resides within the right null-space of the PCM, which means that all check nodes evaluate to zero when the PCM is linearly combined with a codeword.

### FEC-Decoding

Decoding of LDPC codewords is usually performed based on one of the many variants of the Sum-Product-algorithm (SPA), which can be best understood in terms of a message exchange between variable nodes and check nodes. Variable nodes are receiving L-values from the channel via the demapper and the check-nodes to which they are connected. Variable node processing consists of the summation of all incoming L-values and sending the resulting sum reduced by the original check-node message back to the check-node. This can be considered as a vertical FEC-decoding step. Conceptually check node processing consists of performing the check-node sum on the incoming variable node messages (for L-values this is a soft-xor operation) and sending back the check-node sum reduced by the original variable node message. This can be considered as a horizontal FEC-decoding step. The reduction in each step by the original message ensures that extrinsic information is passed between nodes.

For completeness' sake it is worth mentioning that the performance of LDPC codes can be impaired by an error floor at high SNR which is caused by unfavorable message feed-back, i.e., messages are

not truly extrinsic after a few iterations. Hence, frequently LDPC codes are paired with an outer BCH-code which can efficiently detect and correct a fixed number of residual bit errors.

For traditional BICM-blocks (i.e., without WiB) the sequence of receiver operations is such that a received FEC-block is demapped once and bit-deinterleaved once, which is followed by multiple FEC-iterations which consist of several cycles of vertical and horizontal FEC-decoding steps.

The envisaged scheduling for JIDD is different: From a high-level perspective, demapping of the first transmitted signal is followed by single step FEC decoding of the first signal. Then demapping of the second transmitted is making use of the obtained soft information of the first transmitted signal and this is followed by single step FEC decoding of the second signal. This process is repeated with the difference that now the first demapper has access to soft-information about the second transmitted signal. Repetitions of this process are continued until a fixed number of iterations is reached or the codewords are detected successfully.

Please note that JIDD for the demodulation of WiB-signals can also be considered as a generalization of BICM with iterative decoding (BICM-ID), which is a technique based on the exchange of soft information between demapper and decoder.

With a more detailed view, demapping of the first signal yields L-values for the first signal,  $L_{E,Det}^1$ , which are then passed through the bit-deinterleaver  $\pi_1^{-1}$  yielding L-values  $L_{A,FEC}^1$ . They serve as the basis for FEC-decoding which consists of a vertical FEC decoding step and a horizontal FEC-decoding step for the first signal. By summing all newly obtained check-to-variable node messages, the extrinsic soft-information for the first transmitted signal,  $L_{E,FEC}^1$ , is obtained. After bit-interleaving by way of  $\pi_1$  it serves as a-priori soft-information,  $L_{A,Det}^1$ , for the demapping of the second transmitted signal.

Demapping of the second signal yields L-values for the second signal,  $L_{E,Det}^2$ , which are passed through the bit-deinterleaver  $\pi_2^{-1}$  yielding L-values  $L_{A,FEC}^2$ . They serve as the basis for FEC-decoding which consists of a vertical FEC decoding step and a horizontal FEC-decoding step for the second signal. By summing all newly obtained check-to-variable node messages, the extrinsic soft-information for the second transmitted signal,  $L_{E,FEC}^2$ , is obtained. After bit-interleaving by way of  $\pi_2$  it serves as a-priori soft-information,  $L_{A,Det}^2$ , for the demapping of the first transmitted signal.

After this first full set of iterations, computing the extrinsic information at the demapper output slightly changes from the initial round. Now a subtraction of the a-priori soft information,  $L_{A,Det}^1$  and  $L_{A,Det}^2$ , from the demapper output is required, since they are no longer zero as during the initial first iteration.

#### *Bit-Deinterleaving*

The bit-deinterleavers are denoted by  $\pi_1^{-1}$  and  $\pi_2^{-1}$ . They route the extrinsic L-values computed by the demappers to the FEC-decoding stages. To appreciate the importance of bit-interleaving one should understand that L-values of codebits may have different reliability levels depending on their position within a cell. Similarly, the variable nodes of an irregular LDPC code have different degrees or connectivity levels within the graph representing the parity check matrix. The bit-interleaving is

thus connecting L-values with different reliability to variable nodes of varying connectivity and influences the convergence behaviour of the whole BICM-block.

### 3.3.7. Power Splitting

From the view-point of a receiver in a reuse-1 network the received signal is equivalent to that of a signal at a base-station received in a cell from multiple UEs. Hence, the concept of rate regions as described in section 3.2.5 applies. In this context, to maximize the broadcast capacity across the whole network it is desirable to achieve the sloping line of the rate regions which is characterised by identical rates from each transmitter.

A well-known technique to achieve operating points on the sloping line is rate splitting. Here, the rate of any given transmitter is an average of two or more rates. Such an average rate can be obtained by a transmitter which employs two or more codes with different rates in orthogonal resources (frequency slots or time slots).

Since rate and power are related according to the Shannon capacity formula, an alternative to rate splitting can be power splitting in which a single FEC-code is employed from any given transmitter, but it is split over multiple frequency -bands (sub-bands or sub-carriers) and in each sub-band a different power is applied. An added benefit of this approach is that a single FEC-code spread across multiple sub-bands can exploit frequency-diversity.

This section presents an overview of the concept and some results; more information will be published in [10]

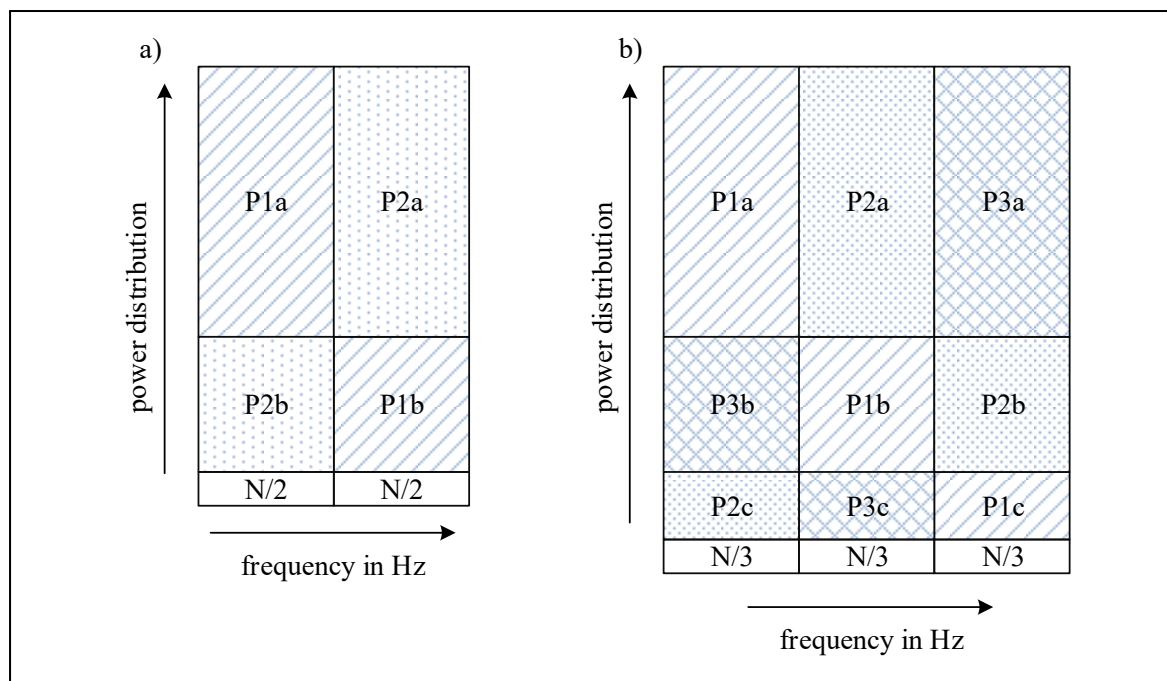


Figure 10. a) Concept of power splitting for two sub-bands, b) power splitting with three sub-bands

Figure 10-a illustrates the concept of power splitting for two sub-bands. A first transmitter splits a FEC-block in two parts and transmit the first part with a power  $P_{1a}$  in a first sub-band and the second part with a power  $P_{1b}$  in a second sub-band. Note that in this example  $P_{1a} > P_{1b}$  and the total power  $P_1$  equals the sum of  $P_{1a}$  and  $P_{1b}$ . Note further that for equal powers ( $P_{1a}=P_{1b}$ ), power splitting degenerates to plain reuse-1, i.e., no power splitting. The concept of power splitting can be easily extended to more than two sub-bands. An example for three sub-bands is shown in Fig. 10-b.

In Figure 11, the effects of power splitting are illustrated. We assumed two sub-bands used by a wanted signal  $C$  and an interfering signal  $I$ , i.e., the concept as depicted in Figure 10-a. The power splitting ratio is defined as  $\rho = P_{1a}/P_{1b} = P_{2a}/P_{2b} > 1$ .

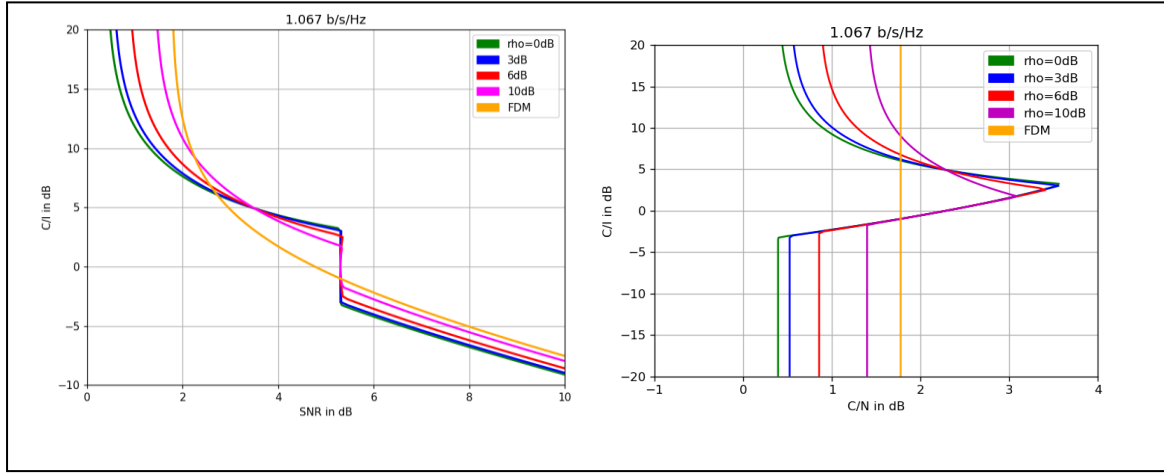


Figure 11: For two Gaussian signals with wanted power  $C$  and interferer power  $I$  in AWGN at different power splits  $\rho$  the 1.067 bit/s/Hz-contours are shown. To the left, the x-axis shows SNR and to the right the same is shown but with  $C/N$  as x-axis. The orange line shows for reference the performance of strictly orthogonal sub-bands in an FDM manner ( $\rho$  towards  $\infty$ ).

The aim of power-splitting is to use a single FEC code and spread it over multiple frequency sub-bands with varying power and in that way benefit from frequency diversity. The achievable rate of such a system can be obtained by averaging the capacity for each limit (JD, SIC and half-sum-capacity) across the sub-bands and then applying the max-min rule mentioned earlier to the resulting capacities:

$$C = \max\left(\min\left(\frac{C_{sum}}{2}, C_{10}\right), C_{12}\right)$$

The 1.067 bit/s/Hz-contours (corresponding to QPSK rate 8/15, with which they will be compared later) are shown in Figure 11 for various power splits  $\rho = \{0, 3, 6, 10\}$  dB. For reference purposes, also the performance of traditional FDM is displayed for which a Gaussian signal utilises only a single sub-band and separated from co-channel signal.

For a fair comparison, the results on the left are shown with respect to the SNR available to the receiver. For the orthogonal FDM case we have assumed  $SNR = (P_1 + P_2)/(2\sigma^2)$ , that is all signal power is considered useful. ( $\sigma^2$  is the noise power in each subband). For the power-splitting case,

we have assumed  $\text{SNR} = (P_{1a} + P_{2a} + P_{1b} + P_{2b})/(2\sigma^2)$ , i.e., it is the ratio of the sum signal power and sum noise power across the sub-bands. By this definition the CNR in each sub-band will be  $\text{CNR} = (P_{1a} + P_{2b})/\sigma^2$  and  $\text{CNR} = (P_{2a} + P_{1b})/\sigma^2$ . The vertical axis displays the C/I defined as  $\frac{C}{I} = \frac{P_1}{P_2} = \frac{P_{1a}+P_{1b}}{P_{2a}+P_{2b}}$ .

In the contour plot on the right, the horizontal axis shows the C/N of the wanted signal only:

$$\frac{C}{N} = \frac{P_{1a}+P_{1b}}{2\sigma^2}. \text{ The three separate regions, defined by the three different limits, are clearly visible.}$$

In general, one can observe for very small and very large C/I that reuse-1 provides a considerable SNR gain over FDM. There are, however, mid-range C/Is between 0dB and 3dB for which excess SNR is required for reuse-1 when compared to FDM. This is in line with, e.g., LDM for which it is well known that the performance improvement over orthogonal access (TDM or FDM) is the more pronounced the larger the SNR asymmetry between served areas. Furthermore, with increasing the power split ratio the SNR loss for mid-range C/Is becomes less whereas it increases for all other C/Is.

In passing we note that the achievable rates in each sub-band could also be characterized by individual rate-regions. So as a variant of rate splitting, power splitting could potentially also be used with individual codes matched to each sub-band. In such a case the total rate of the wanted signal can be obtained by an application of the max-min rule in each sub-band and taking the average over these rates. Interestingly it can be shown, that a power splitting ratio of  $\rho=3$  dB can unequivocally provide an SNR gain across all considered C/Is. This approach, however, would dispense with the benefits of a single FEC-code which is benefiting from frequency diversity and will not be considered further.

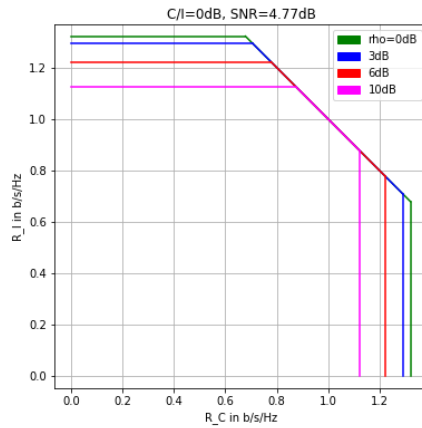


Figure 12. The effect of power splitting on the rate region of Gaussian signals

Additional insight about power splitting can be gained by visualizing the involved rate regions. This was done in Figure 12. At C/I=0dB and SNR=4.77dB the power split is varied between 0 dB and 10 dB. Three observations can be made:

1. The rates achievable by SIC become smaller, i.e., the horizontal and vertical limits to the rate regions shrink downwards and leftwards respectively.
2. Simultaneously, the rates achievable by JD increase, i.e., the corner points of the rate region move rightwards (and downwards) and upwards (and leftwards) respectively.



### 3. The jointly achievable sum-rate remains constant.

Effectively, power splitting allows to trade-off rates achievable by Joint demapping and SIC. If joint demapping is conceptually considered as the receiver being least informed about the interfering signal, and SIC as the receiver the most informed, then power-splitting can shift the balance between JD and SIC. This is also an important aspect for the Joint iterative demapping and decoding which over the course of the FEC-decoding shifts from operating in JD mode towards operating in SIC mode. Power splitting is hence also a means to aid the FEC-decoding either making its first iterations with JD or towards the last iterations with SIC.

#### 3.3.7.1 LDPC decoding

The previous section assumed ideal Gaussian signals. This section will address how much of the capacity is retained when actual constellations and FEC-codes are employed.

For reference, Figure 13 shows the Coded Modulation capacity of two QPSK signals received in a uniform phase channel. The uniform phase channel is characterized by  $h_1[k] = 1$  and  $h_2[k] = e^{j2\pi\varphi[k]}$ , with  $\varphi[k]$  uniformly distribution between 0 and 1. The derivation of these results is not presented in this document, but requires evaluation of the Mutual Information for the combined constellation arising from adding together the wanted signal and interferer, averaged over the channel realisations, using the conditional or marginal probabilities as appropriate for each of the three pentagon limits.

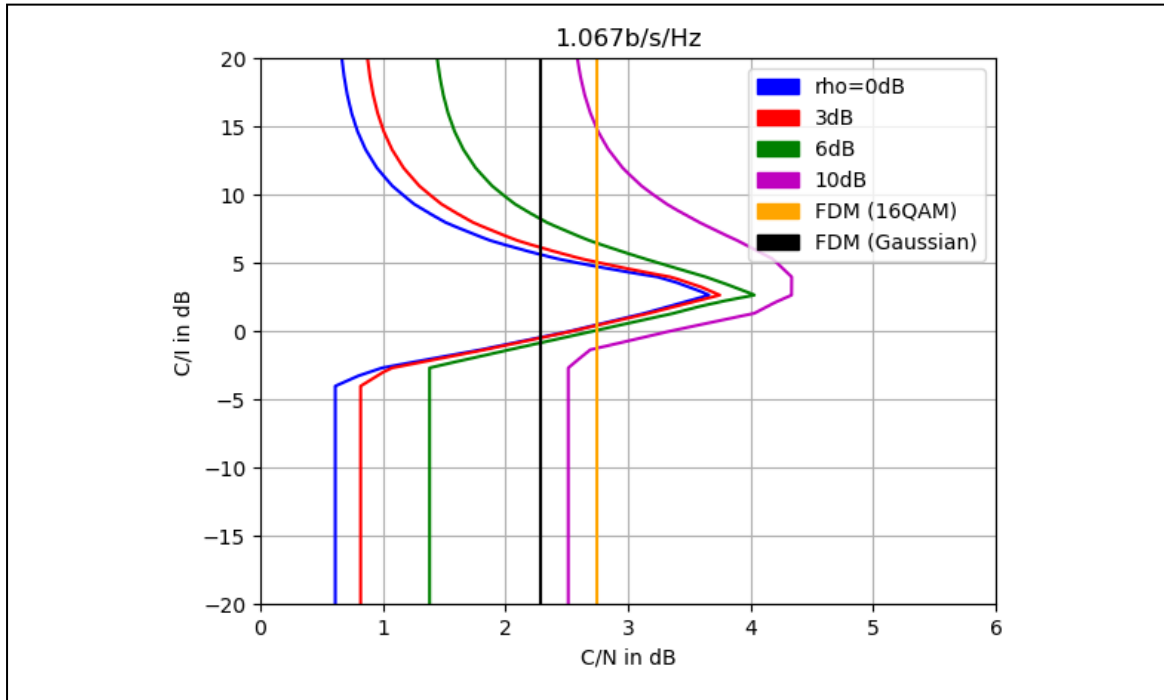


Figure 13. For two QPSK signals with wanted power  $C$  and interferer power  $I$  in a uniform phase channel at different power splits  $\rho$  the 1.067 bit/s/Hz-contours (for a modcod with QPSK and coderate 8/15) of the Coded Modulation capacity are shown. The black line shows for reference the performance of FDM with strictly orthogonal sub-bands and Gaussian signalling, and the orange line for 16-QAM signalling.

The Coded Modulation capacity (CM capacity) serves as an upper-bound to the BICM capacity and it is assumed that the SNR loss between them is small, if not negligible. The CM capacity behaves largely similar to Shannon capacity in that, for a given power splitting ratio, the highest C/N gains compared to strictly orthogonal sub-bands (FDM) are obtained for large and small (i.e. negative) C/I. A different behaviour can be observed for mid-range C/Is for which – unlike in the Gaussian signal case – increasing the power splitting now also results in a C/N loss.

Two effects are responsible. Firstly, this can be explained best with the help of very large power splits which place literally QPSK cells in only one sub-band, whereas the other sub-band remains almost unmodulated. Under these FDM-like circumstances, QPSK is beginning to saturate: it would need to deliver almost its uncoded rate of 2b/s/Hz in the higher-power sub-band to give an average of 1.067b/s/Hz. Secondly, in terms of the rate region joint iterative decoding is generally required at these C/I and C/N conditions to provide 1.067 b/s/Hz. In other words, the rate tuple lies on the sloping line of the rate region and the sloping line for purely Gaussian signals outperforms that of QAM signals. Correspondingly, the C/N must be higher for QAM signals to still achieve 1.067 b/s/Hz. This apparently suggests that there is no benefit to power splitting in the Coded Modulation case. However, for practical FEC codes, there is a benefit in terms of error performance as will be seen.

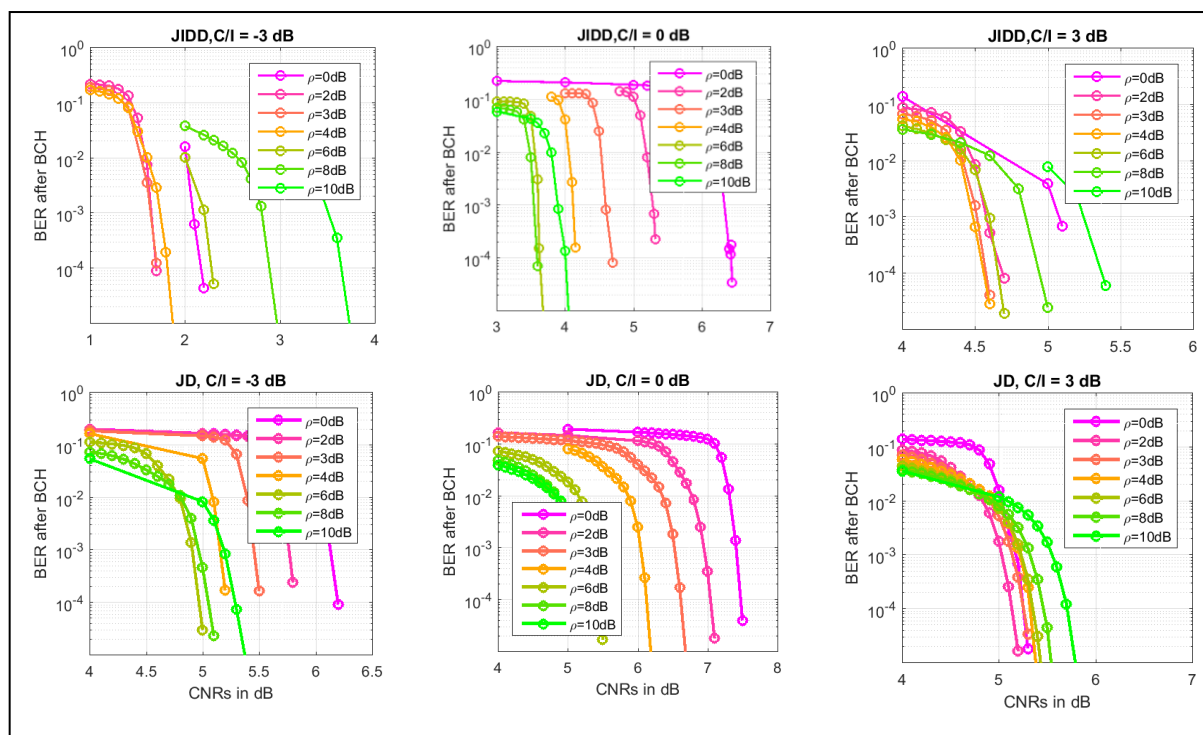


Figure 14. BER performance QPSK+QPSK in the uniform phase channel at C/I={-3,0,3}dB and power splitting ratios from 0 to 10dB. The upper rows show JIDD performance, the lower row JD performance.

Next, FEC simulations are considered for the same uniform phase channel. QPSK is used for both wanted and interfering signal and the long LDPC code of code rate 8/15 from the latest ATSC 3.0 standard is used. FEC-decoding is performed with a maximum of 50 iterations. Figure 14 illustrates coded BER performance for the uniform phase channel at various C/Is and power splitting ratios. The upper rows show Joint iterative demapping and decoding (JIDD) performance. For comparison, the

lower row shows joint demapping (JD) performance. For the JD, it is assumed that the receiver knows the involved signal alphabet, but no attempt at SIC is made and one-time demapping of the wanted signal is followed by sum-product FEC-decoding with a maximum of 50 iterations.

Although in direct comparison to JIDD, JD performs inferior, the following observations regarding JD are interesting. At C/I smaller than or equal to 0dB, power-splitting improves the JD performance. In the considered cases, C/N gains between 1.2 and 2 dB seem possible. This is in-line with the observation made earlier that the rate regions morph with the power splitting and SIC rate and JD rate are exchanged for one another. If, however, the C/I is positive (in dB), then larger power splits affect the performance negatively, since the C/I and the power-split are working against each other.

The BER performance of JIDD is generally improved by power-splitting throughout all considered C/Is. The condition of 0dB C/I, usually perceived as critical, is considerably helped by a higher power split for which an C/N gain of 3dB is possible. Overall it would seem that a moderate power split between 2dB and 3dB is helpful for the JIDD performance. And, roughly, when comparing the achievable CNRs with those for Gaussian signals, then the SNR loss due to imperfect FEC codes seems to lie between 1.1 dB and 1.3 dB, see the table below.

C/I	$\rho$	JIDD waterfall C/N	Shannon pentagon C/N	Difference
-3dB	3dB (best)	1.6dB	0.5dB	1.1dB
0dB	6dB (best)	3.5dB	2.2dB	1.3dB
+3dB	3dB (best)	4.7dB	3.5dB	1.2dB

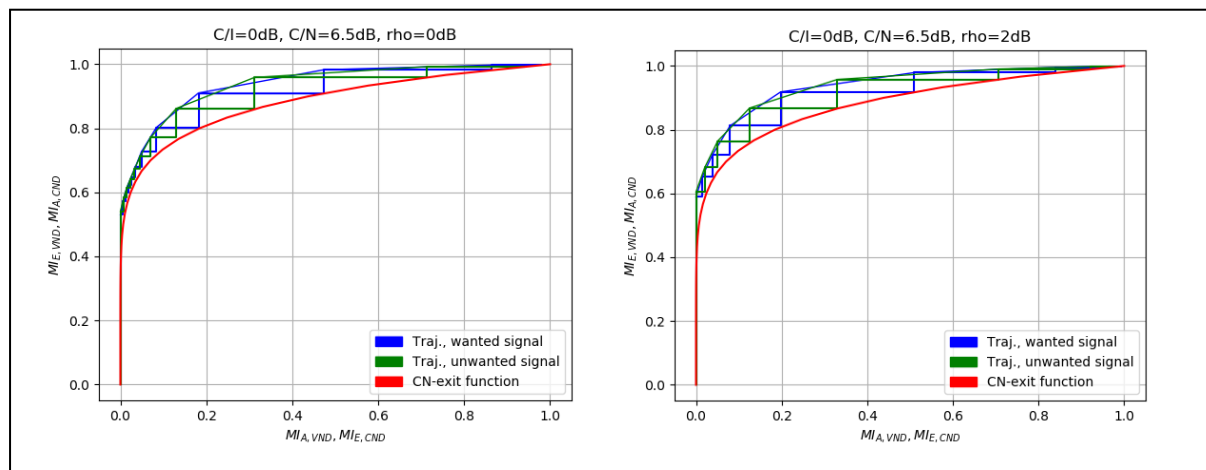


Figure 15. EXIT functions at C/I=0dB and C/N=6.5dB for power splits 0dB and 2dB

As a final point, one may wonder why a power splitting ratio of 0dB has the highest CM capacity but not the best bit-error performance with practical codes. This problem can be explained with EXIT-charts (see Figure 15). Here, the EXIT-curve for the check-node messages is displayed as red curve. For the purposes of this report this EXIT function is fixed since a particular LDPC code was used to which it applies. For the figure on the left hand-side a power split of 0dB is used and one can

recognize already a choking point early during the iterations. To the right-hand side, a power split of 2dB is displayed which moves in effect the VN exit functions upwards and relieves the choking point considerably. Thus, power-splitting can be seen as an additional tool for code-design and further gains appear possible by curve matching techniques.

#### **4. Networks studied**

As highlighted in earlier sections, WiB seeks to obtain greater spectral efficiencies through complementary changes to both the physical layer and transmitter network design. Network simulations which combine these two aspects have therefore been extensively used by the group in order to find out how well WiB, and its various techniques, might perform compared with conventional DTT systems. Two different simulation methods have been used:

- **Regular hexagonal grid network** simulations using the ITU-R P.1546 [11] propagation model
- **'Real world' network** simulations with real transmitter details, terrain based propagation models, ground clutter and population databases.

The two methods each have their strengths and weaknesses, for which there is more information below, but due mainly to their simplicity and speed, hexagonal grid simulations have been most extensively used. Combined with the common simulation framework established by TM-WiB [TM-WiB0065], hexagonal grids have enabled the rapid development and simulation of ideas which can be easily shared and peer reviewed by other members of the group.

By their very nature, regular hexagonal networks are stylised representations of reality, and for the reasons discussed below, the results from these simulations may not always carry over to the real world. More accurate techniques, such as the UK Prediction Model (UKPM), have therefore been used in order to determine whether the benefits of the more promising WiB techniques, uncovered in the hexagons, may also be expected in practice.

A brief overview of the two methods, their advantages and limitations is provided below.

##### **4.1. Regular hexagonal grid networks**

As the name suggests, regular hexagonal networks are an idealised representation of transmitter networks in which the transmitters are arranged in a homogenous way. Due to their simplicity and regularity, hexagonal networks have been helpful for studying WiB's various techniques under controlled conditions where it is relatively straight-forward to isolate one technique from another in order to identify any benefits that may arise.

Figure 16 illustrates the layout of the 91 site network that was routinely used by TM-WiB for consistency and ease of comparison.

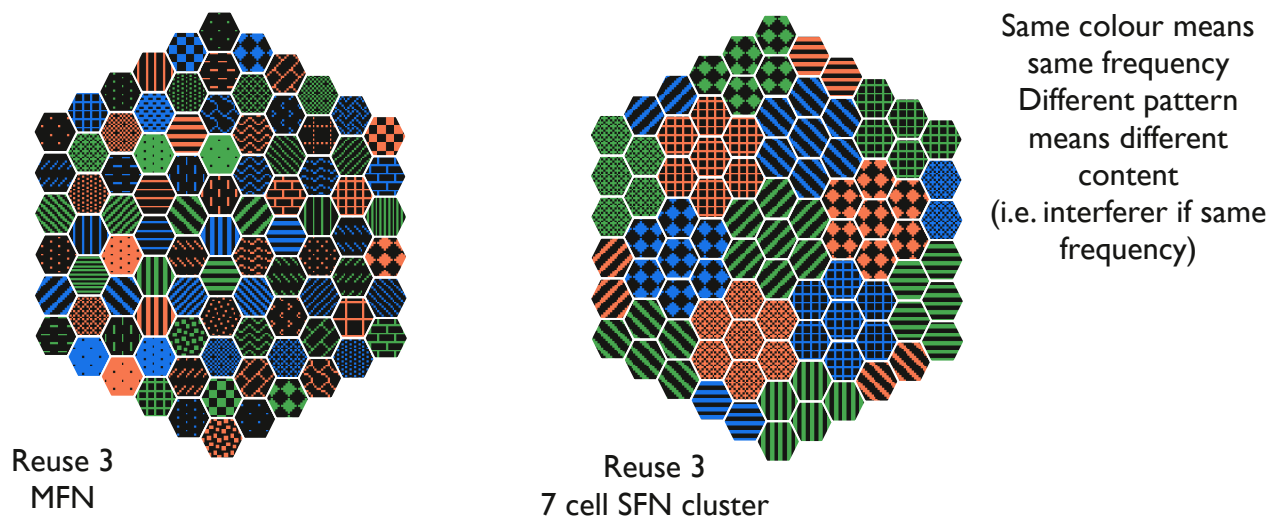


Figure 16 Comparison between hexagon networks for MFN and SFN, re-use 3

Regular hexagonal network simulations combined with ITU-R P.1546 have a number of characteristics:

- They are limited to certain regular frequency re-use patterns e.g. 3, 4 and 7. See figure 17. i.e. repeated elemental patterns that avoid adjacent cells being assigned the same colour.
- Frequency re-use three is possible. This is not commonly practical in the real world where four colours are needed to avoid adjacent cells of the same colour.
- Frequency re-use patterns five and six, re-use patterns commonly found in the real world, are not possible.
- The mean field strength from each site always decreases with distance. ITU-R P.1546 is a monotonic function of distance.

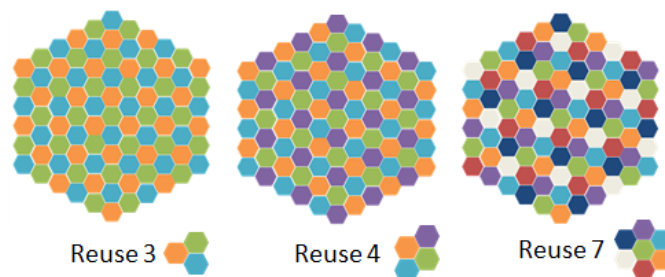


Figure 17 Different Frequency Re-Use Patterns Possible in Hexagonal Networks (with no same-colour adjacent cells)

Hexagonal network simulations, although an idealised abstraction of real world networks, have a number of attractive properties that can make them a useful first-step tool for assessing potential new physical layer and network planning techniques:

- Simulations can be done very rapidly with ITU-R P.1546.
- The symmetry of regular networks often allows computations to be done for a single receiving location. This significantly reduces simulation time, allowing different ideas to be quickly assessed.
- Due to the speed of the calculations Monte Carlo techniques can be incorporated relatively easily, enabling the effects of signals' time and location variations to be studied under different assumptions.
- Different organisations can easily replicate, confirm and review results within a common framework to which they all have access.
- The particular circumstances of one country compared with another's can be removed (e.g. international frequency coordination requirements and topography).

Although simulations based on regular hexagonal networks are a useful first-step in assessing the relative merits of various WiB techniques, they do have a number of limitations, and in the end it is necessary to confirm the outcomes of these studies with more detailed 'real world' techniques. These are discussed in the next section.

#### **4.2. Real World Simulations**

In contrast to regular hexagonal networks, the conditions found in the real world are often far from uniform. For example, the distance between sites in a practical network is not constant, transmitter heights vary from one site to another, and each site often has distinct radiated powers and antenna patterns. These heterogeneous features, combined with real terrain including mountains, valleys and sea will influence the coverage of a network. As real-world simulations include all of these factors they will give a better view of what WiB may offer in practice. Real world simulations are therefore indispensable.

Real world simulations are, however, significantly slower than those done with regular hexagonal grids. It has therefore been impractical to simulate all of the ideas developed by TM-WiB during the study with real world simulators. They have therefore been limited to confirming the results of the most promising ideas developed from the hexagon based studies.

Additionally, the proprietary nature of real world coverage simulators, and the particular circumstances of one real world network compared with another can make direct comparisons of results from different sources difficult. It can therefore be unclear whether results from a network in one country, for example, would be representative of the results in another.

A combination of the two techniques has therefore been used by TM-WiB in order to highlight trends and outcomes and to gain confidence that they would be possible in the real world.

#### **4.3. Coverage Simulation Background Information**

This section provides background information on a number of coverage related factors that are important for this study

##### **4.3.1. Location Variation**

In order to calculate the coverage of a network the entire coverage area is normally broken down into adjacent small square areas, or pixels, with sides of 100m. The coverage for each pixel in the

network is then computed based on the mean wanted and interfering signals within it, as well as the extent to which they vary from one location to another within the small area of the pixel.

A suitable prediction model is used to calculate the mean signal levels for each pixel, while measurements show that the signals from a given transmitter vary from one location to another within the pixel due to local topological features such as irregular terrain, buildings and trees. This variation can be closely modelled by a log normal distribution with zero mean and 5.5dB standard deviation.

The probability of achieving reception within each pixel can then be computed by treating the signals from each transmitter as log-normally distributed random variables whose mean is taken from the prediction and whose standard deviation is the 5.5dB discussed above.

TM-WiB have used two main ways of taking into account the location variation in computing the probability of receiving a viable service within a pixel: closed-form and Monte Carlo. Under the same assumptions, both are nominally equivalent but they each have characteristics which often make one better suited than the other to the particular circumstances at hand. As both have been extensively used in this report the following sections contain some background information on them.

#### **4.3.1.1 Closed-form calculation**

In conventional planning studies, there is a wanted signal, and a set of interfering signals plus noise. The wanted signal itself may come from more than one transmitter (in the case of an SFN). The signal from each transmitter provides a signal strength that is assumed to follow a log-normal distribution. The wanted signal strength in any given location is therefore the sum of a number of random variables each following the log-normal distribution, and the unwanted signal strength is a sum of a different set of log-normal variables. (The level of thermal noise is treated as an additional log-normal random variable with zero variance). The sum of two or more log-normal variables is not itself log-normal, but it can be approximated by a new log-normal distribution whose parameters can be estimated by one of several well-known techniques including Schwartz and Yeh [12] and Fenton-Wilkinson [13].

Once the wanted and unwanted signals have been approximated by log-normal variables, the ratio of signal-to-interference-plus-noise (SINR) can be considered. Since the log-normal distribution is equivalent to a *normal* distribution of dB values, and the ratio can be expressed as a *difference* of the dB values, the SINR in dB is a new random variable equal to the difference between two normal variables. It is a standard property of the normal distribution that the difference of two normally distributed variables is itself normally distributed: the mean of the result is equal to the differences in the means and the variance is equal to the sum of the variances.

The SINR in dB, for locations within a given pixel, is therefore reduced to a single random variable with a normal distribution. The SINR exceeded for a given percentage of locations can therefore be calculated simply by subtracting the appropriate number of standard deviations from the mean value.

This approach has the advantage that the calculations can be performed very quickly. The Monte Carlo approach described below can also be used for the conventional case: it is more accurate but much slower.

#### 4.3.1.2 Monte Carlo calculation

In most of the WiB scenarios, the receiver is assumed to be able to take into account the modulation and/or coding of one or more interferers in addition to the wanted signal. As a result, interference and noise have different effects on the available capacity: this is illustrated by the capacity contours presented in sections 3.2.4 and 3.3.5. In the case of a single interferer, the S/N and S/I ratios need to be considered separately: they form a two-dimensional distribution. This means that, unlike the conventional case, there is no longer a single value corresponding to, say, 70% of locations. Different locations correspond to different realisations of the 2D distribution, and each have their own particular combination of S/N and S/I. Depending on the receiver technique or theoretical limit being assumed, this will result in a particular capacity value.

The most straightforward way to determine the capacity for a given percentage of locations is a Monte-Carlo approach: a large number of variates are generated corresponding to different realisations of the 2D distribution; in each case the ergodic capacity is found for the combination of S/N and S/I at that particular location; and a histogram of capacities is produced. The capacity for the desired percentage of locations is then determined from this histogram.

For this case (a receiver technique that can take account of a single interferer), the capacity for a given technique depends on four parameters: the mean and standard deviation of each of the S/N and the S/I. Interferers that are not taken into account by the receiver are lumped into the S/N together with the thermal noise. If the capacity for a large number of pixels needs to be processed, as in the case of the UKPM (see section 5.3), it proved worthwhile and feasible to calculate a 4-dimensional lookup table in advance.

A 4D lookup table generated in this way, with an appropriate range and resolution in each dimension, has a size roughly the same order of magnitude as the number of pixels in the UKPM. However, it has additional advantages over carrying out the Monte-Carlo simulation for each pixel: it makes it much quicker to repeat coverage runs with different parameters (e.g. transmit power, guard interval, etc.), and the table itself can be inspected by plotting surfaces and slices at different parameter values, both to confirm that it has been generated correctly and to gain insight into its behaviour and features.

For techniques that can take into account more than one interferer, such as successive-interference cancellation with two cancellation steps, or the “Shannon Diamond” limit (see section 3.2.5), the lookup table would need to be six-dimensional: the storage requirements and calculation time would be prohibitive. For such cases, the Monte-Carlo simulation had to be carried out on a pixel-by-pixel basis.

The figure 18 below shows an example of the effect of location variation on capacity. The dashed ellipses are contours of equal probability density for the 2D distribution in (C/N, C/I) space. They are elliptical because the standard deviations of C/N and C/I are different. The solid lines show contours of capacity for a particular receiver scheme (Joint Demapping with QPSK in the IID Rice channel). The capacity under these conditions, for 70% locations, turns out to be 1.15bps/Hz: as can be seen, the



corresponding contour divides the distribution such that 70% of the distribution is on one side and 30% on the other. The red dots represent the 30% of realisations that fell below a capacity of 1.15bps/Hz and the blue dots show the 70% that exceeded this capacity.

As can be seen, the capacity at the median of the distribution is 1.6bps/Hz. This shows the very significant penalty arising from location variation, even at 70% locations. The penalty for 95% locations would be even greater. The impact of location variation appears to be greater for WiB than for conventional networks. At the lower S/N and S/I values present in WiB networks, a given reduction in S/N or S/I results in a greater percentage reduction in capacity.

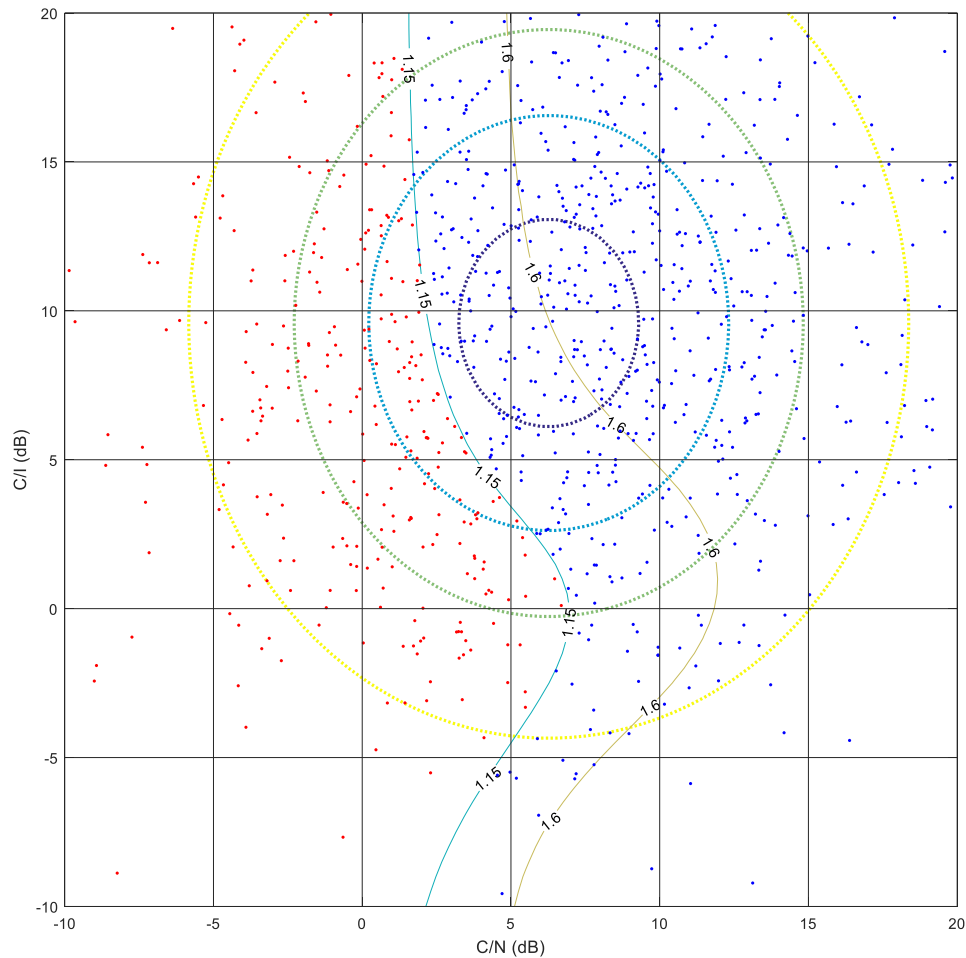


Figure 18. Capacity contours for joint demapping and the effect of location variation

In the figure, and in the generation of the 4D lookup table, it is assumed that the S/N and S/I are independent random variables. This is not strictly correct, since both variables contain S, the level of the wanted signal. Hence the ellipses should have their major axes aligned more towards the up-right diagonal. Taking this into account correctly would increase the dimensionality of the lookup table, again making it unfeasible. The inaccuracy can be avoided when carrying out separate Monte Carlo simulations for each pixel, by treating the wanted, interferer and other unwanted signals as three separate variables to be realised. For the UKPM this was found to have a small but significant effect on the available capacity.

#### 4.3.2. Time Variation

The propagation of signals is affected as conditions in the atmosphere change over time. At a given location, therefore, the power of a signal received from any particular transmitter will not be constant – it will also vary with time. Although signal levels continuously vary, it is well documented that for short durations, e.g. for 1% of the time, signals much higher than the mean can be received – see figure 18. In order to ensure that the desired signals within a network can be reliably received (e.g. for 99% of the time) the changes in propagation must be taken into account [14].

Such signal variation has been incorporated into a majority of the studies in the following way:

- Fix all the wanted signals at their mean, or 50% time values.
- Fix all interferers at their 1% time values, typically appreciably higher than the mean value.

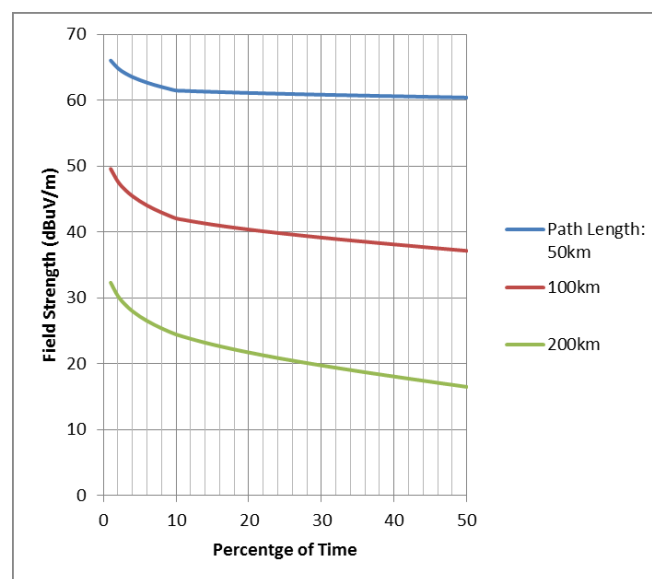


Figure 19 ITU-R P.1546 Field Strength Exceeded for Shown Percentage of Time. ERP = 47dBW, Tx Effective Height = 250m, Rx Height = 10m, 100% Land Path.

The simplifications above are widely used in network planning as they significantly ‘speed up’ the computation time of a network simulation. They may however be somewhat conservative as measurements suggests that the time variation of signals is not fully correlated [15]. Indeed, studies done outside the group [16] indicate that a more detailed model of time-variation would lead to higher capacities, particularly for bandwidths wider than 8MHz. Furthermore [TM-WiB0091 and TM-WiB0037] support these findings.

Based on these references it should be noted that WiB is expected to further benefit from a more detailed assessment of time variation. But, for the purposes of this report, time variation has been set aside for consideration at a later date, and it has not been included in the main studies or the findings in this report. The findings of this report are based on the two time-variation bullet points above.

#### **4.3.3. Wanted/Best Transmitter**

In simulations involving directional receiving antennas it is necessary to choose the direction in which the antenna should point. During the course of the TM-WiB study mission a number of different methods were identified which can be used to help decide, each with the potential to produce different results. It is therefore important to know which method has been used so that the studies can be correctly understood. The methods that were identified by TM-WiB are described in more detail below.

##### **4.3.3.1 Wanted Transmitter**

In this method the receiving antenna is aligned to a specific site – the wanted transmitter – before the simulations are started, and this alignment is maintained throughout. The wanted and interfering signals at the receiving location are then adjusted according to the appropriately aligned receiving antenna pattern.

This method is most useful in simulations involving border locations where it is necessary to receive a signal from the desired region, or country. However, this method may have a tendency to underestimate the coverage at some locations as other alignments, which may provide better coverage, would not be allowed.

##### **4.3.3.2 Best Transmitter**

The best transmitter methodology contains a number of sub-options, all of which would typically produce better coverage than would come from the wanted transmitter method, but none would guarantee the reception of the signal from the desired region or country. In all cases the best available signal would be chosen, regardless of where the signal has come from. The sub-options that TM-WiB has identified are discussed below.

###### **4.3.3.2.1 Best Transmitter per Pixel**

In this method it is implied that all receiving aerials within a pixel would be aligned to a single, best serving transmitter. Receiving aerials in different pixels may be aligned to different transmitters. The basic algorithm is described below.

At each pixel the receiving antenna is, in turn, aligned to each permitted transmitter in the network. For each alignment the mean coverage within the pixel is computed with the best transmitter's coverage assigned to the pixel.

For example, for a particular pixel in the 91 site hexagonal network where any signal could be considered to be a viable wanted transmission, the antenna would, in turn, be aligned to each of the transmitters and 91 coverage values would be computed. The highest of these values would then be taken as the coverage of the pixel, and the transmitter providing that coverage would be the best transmitter.

Although this method can be carried out with Monte Carlo, it is well suited to analytical approaches (e.g. Schwartz and Yeh or Fenton Wilkinson) based on the mean signal values and their corresponding location variations. The best transmitter per pixel method has been extensively used by TM-WiB for both hexagonal grid and the real world simulations involving the UKPM.

#### **4.3.3.2.2 Best Transmitter per Location**

In this method the receiving aerials within a pixel may be aligned to different transmitters, whichever is found to be best. A description of how this method may be implemented is described below.

An appropriately large number of receiving locations (e.g. 100,000) are considered within each pixel. At each of these locations the signal level from each transmitter is generated based on its mean and a random realisation of its location variation. The receiving antenna is then aligned to each transmitter in turn, and the coverage is computed. The best transmitter's coverage is then assigned to the location in question and the process is repeated for each location. A histogram of coverage is thus created and the value for the appropriate coverage percentile obtained. This becomes the final coverage for the pixel, and the process is repeated for all other pixels in the calculation. In this method it is not necessary for all receiving aerials within the pixel to be aligned to the same transmitter station; indeed in some pixels it is likely that receiving aerials at different locations would be aligned to different transmitters, depending on which is best.

However, note that for the cases involving clusters of transmitters in an SFN, when choosing transmitters to align the receiving antenna, only those transmitters within the SFN containing the pixel are considered to be candidate transmitters for the wanted signal, and all others are considered as interference.

Due to the greater flexibility in which direction the receiving antenna can point, this method is likely to produce higher coverage than the Wanted and Best Transmitter per Pixel methods.

Monte Carlo based simulations are well suited to this methodology.

The UKPM based simulations were not carried out in this way.

#### **4.3.3.3 Best Direction**

It would also be possible to further generalise the two Best Transmitter methods above by permitting the receiving antenna to point in directions other than directly towards one of the transmitters. It may be possible to obtain better coverage by pointing the aerial somewhere between two transmitters, rather than directly towards one or the other.

As this method would significantly increase computation time it was not used in the study mission. Furthermore, conventional planning methods rely more commonly on the methods mentioned above, and in order to aid a fair comparison with existing coverage levels, those methods have been used.

#### **4.3.4. Worst point in a hexagonal network**

The regularity and symmetry of hexagonal networks allows for the identification of the worst performing pixel, or pixels – the location, or locations within a network where the capacity is lowest. At all other locations the performance would be better, and therefore the worst performing pixels may be considered to limit the performance of the network overall. Improving the performance of these pixels would improve the performance elsewhere too.

Identifying the worst performing pixels in a particular network enables coverage comparisons to be done extremely quickly, as only the performance of these pixels needs to be considered, as opposed

to the performance across all of the many pixels comprising the entire coverage area. Symmetry in the network then leads to the identification of a single worst pixel, further reducing the computation time.

Although it may not always be the case, often the worst pixel is at the corners of three cells, or a triple point, as shown in figure 20. At points such as this the SINR is often at its lowest. However, care must be taken to ensure that this is indeed the worst point for all combinations of parameters that may be changed in the various different studies. Simulations over a wider area should therefore be used to confirm that the worst point has been correctly identified for the studies at hand.

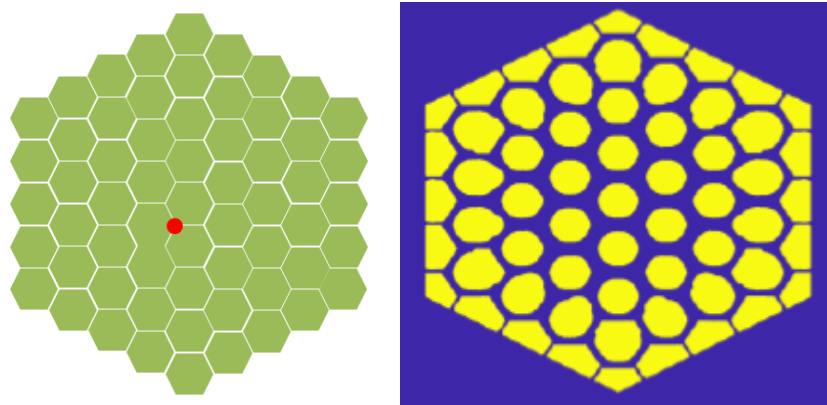


Figure 20. Worst Receiving Point (Left), Coverage (Right): Yellow Shows Coverage to a Given Threshold.

#### 4.4. Coverage Criteria

In order to assess whether sufficient coverage is achieved it is necessary to set criteria which must be met. Depending on their circumstances and requirements the values in table below are widely used by broadcasters, and they have been used in this study.

Scenario	Reception Mode	Location Percentage (%)	Time Availability (%)	Area Coverage	Population Coverage (%)
Widely Used Real World	Fixed Rooftop	95	99	Various	Circa 90 to 99%
UK 'Real World' Planning	Fixed Rooftop	70 <sup>3</sup>	99	N/A	>98.44% <sup>4</sup>
Regular Hexagonal Networks	Fixed Rooftop	95 70	99 99	100 100	N/A N/A
Widely Used and Hexagonal networks	Portable Handheld	99	99	Various	Various

Commonly used coverage criteria

The table shows that, depending on the scenario, different coverage criteria can be used. In order to gain a fair comparison, it is therefore essential to ensure that the same criteria are used when comparing one study to another.

<sup>3</sup> These criteria have been demonstrated in practice to ensure robust DTT coverage in the UK.

<sup>4</sup> This is the population able to receive all three UK PSB multiplexes from the same transmitters.

The table also shows that the requirements for Portable Handheld coverage are more stringent than for fixed rooftop, making the link budget more challenging.

## 5. Results for main scenarios studied

### 5.1. Main results from hexagon network studies

Network simulations were carried out both for WiB networks and for various traditional MFNs and SFNs.

#### 5.1.1. Common network simulation parameters

The simulations presented in this section all used a ‘standard’ ITU-419 [17] receiving antenna template. Section 7.5 discusses the implications of using an “improved” antenna template.

All the simulations used the 50% time value for the wanted transmitter and 1% time values for the interferers.

Unless otherwise stated, the following conditions may be assumed for all hexagonal network studies in this report:

- The transmitters are located at the centre of the hexagons.
- The hexagons are all of the same size.
- The distance between transmitters, or the inter-site distance (ISD), is constant (60km).
- The radiated power (ERP) of all transmitters is the same – normally 47dBW.
- All transmit and receive antennas are of the same polarisation
- All transmit antennas are omnidirectional both horizontally and vertically
- The network is expansive enough to approximate an infinite plane (91 transmitters in most cases – see figure 21).
- The ITU-R P.1546 propagation model (over land) has been used to calculate the field strength of the transmitters at the receiving locations.

For WiB, the relevant capacity calculation from section 3 was applied. For MFNs and SFNs, the capacity was calculated according to the unconstrained Shannon limit (see section 3.2.1), corrected to account for the Guard Interval overhead, and divided by the re-use factor  $R$  to give the overall spectral efficiency  $\eta_{spectral}$  for the network:

$$\eta_{spectral} = \frac{1}{R} \log_2 \left( 1 + \frac{C}{N + I} \right) \times \frac{T_u}{T_u + T_g}$$

#### 5.1.2. MFNs

These were done for a 91 transmitter site network assuming no interference cancellation.

The networks that were simulated are shown in figure 21 . (Note that the re-use 1 network shown is not literally an MFN as all the transmitters are on the same frequency, but they all carry different content and no interference cancellation is applied).

Signals from the unwanted co-channel transmitters were combined using the Schwartz & Yeh method, and the unconstrained Shannon capacity was calculated treating the unwanted signals as

noise. As these are MFNs, the guard interval was set to zero. In practice a very short guard interval would be needed to handle natural multipath, but the impact on capacity would be insignificant.

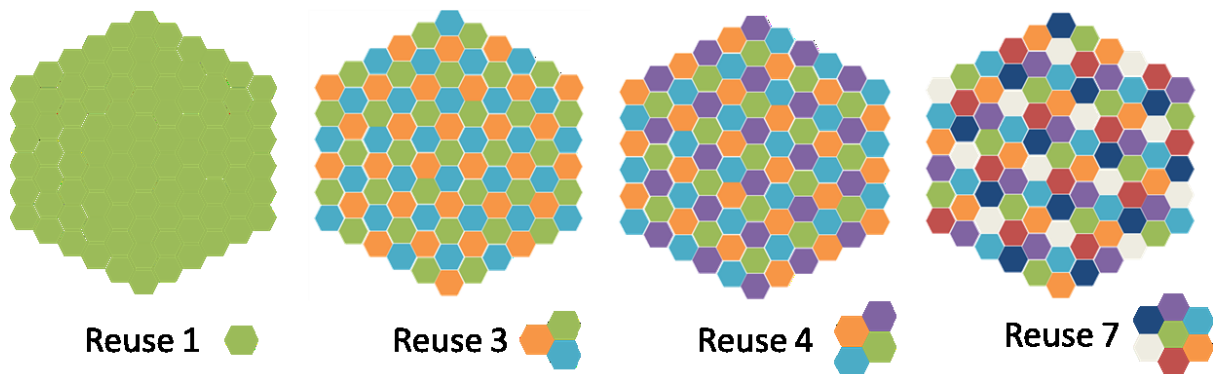


Figure 21. Frequency patterns used for different MFN re-use cases

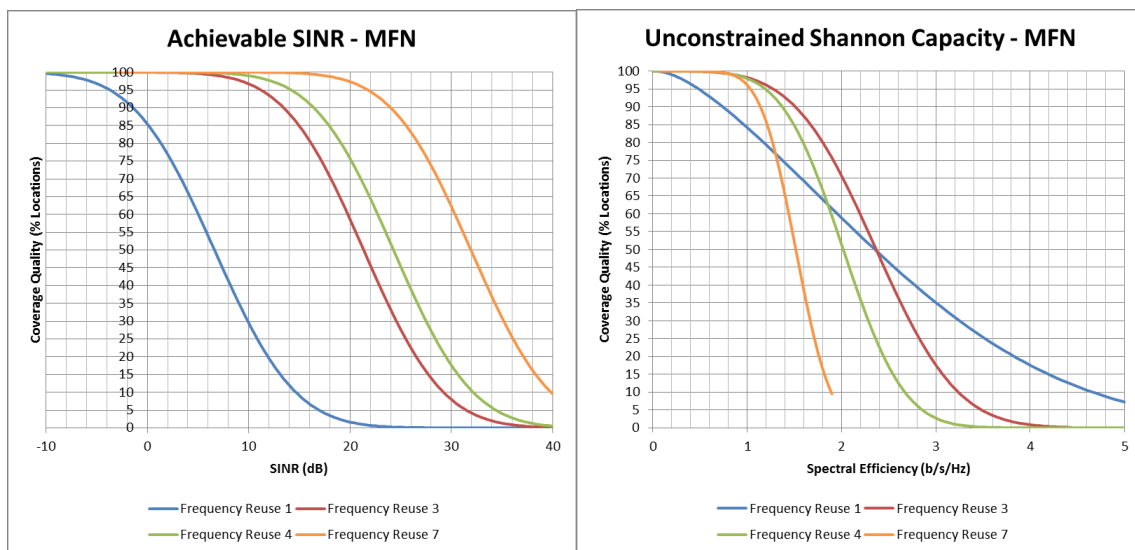


Figure 22. Available SINR and capacity of the hexagonal MFN networks

At the worst performing point, the following unconstrained Shannon Capacities were found:

	MFN shannon capacities (b/s/Hz)			
locations	reuse 1	reuse 3	reuse 4	reuse 7
95%	0.48	1.28	1.2	1.03
70%	1.56	2.01	1.75	1.36

In hexagonal networks, MFNs achieve their highest spectral efficiency at frequency re-use three. However, re-use 3 is not practical in real MFNs; instead a higher factor is needed, usually between 5 and 7.

### 5.1.3. Regional SFNs

A number of regional SFNs were also simulated, with SFN clusters of size 3, 4 and 7 and re-use factors of 3 and 4. The networks are shown in figure 23. There was concern that a larger network may be necessary for these simulations because, in the 91 site network, even the nearest interfering cluster on a given frequency is not always completely included, hence the interference situation may not have been fully represented. The results were compared with those for a larger network with 135 sites. The resulting spectral efficiency was only slightly lower.

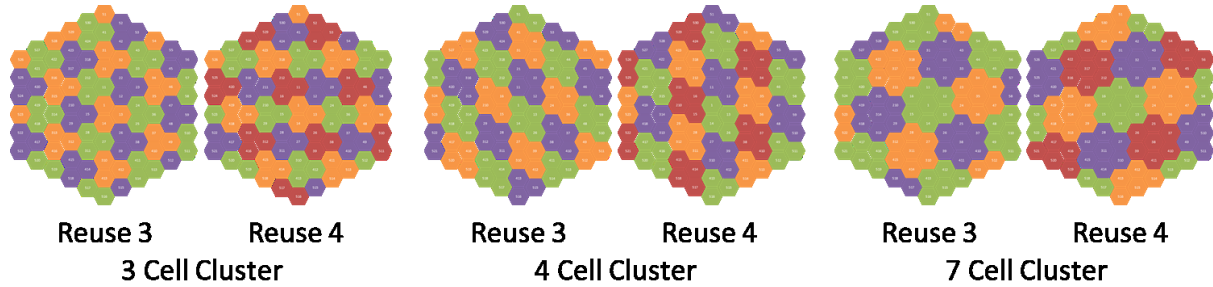


Figure 23. Frequency patterns used for different MFN re-use cases

The guard interval was set according to the size of the SFN cluster so as to ensure that, in the worst case, the delay between the earliest and latest signal from the wanted cluster would be within the guard interval. The guard interval overhead was allowed for in the capacity calculation. See the table below.

Frequency Reuse	SFN Cluster Size	Tu (us)	Tg (us)
3 & 4	3	3584	224
3 & 4	4 & 7	3584	448

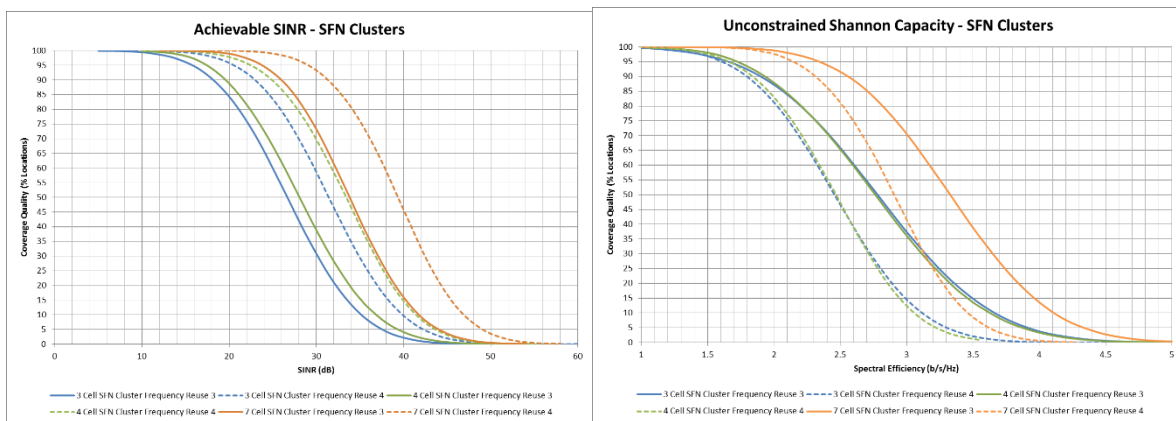


Figure 24. Available SINR and capacity of the hexagonal MFN networks

The following key findings can be noted for the regular hexagonal networks studied:



SFNs also achieve their highest spectral efficiency with frequency re-use three. SFNs, including the guard interval overhead, may achieve higher spectral efficiencies than MFN.

SFNs with larger cluster sizes are more spectrally efficient than smaller cluster sizes.

At the worst performing point, the following unconstrained Shannon Capacities were found:

- 2.35 bps/Hz at 90% location probability for cluster size 7 frequency reuse 3
- 3.0 bps/Hz at 70% location probability for cluster size 7 frequency reuse 3

It should be noted that cluster size 7 may not be practical in all real-world networks where the size of SFN regions could be smaller than seven main stations. Cluster size three or four may be more indicative of some real world conditions.

#### 5.1.4. WiB networks

The WiB networks in figure 25 were simulated. As for MFNs, the network has 91 sites. The receiver is located at the position indicated with the dot with the antenna directed towards transmitter number 1 as shown.

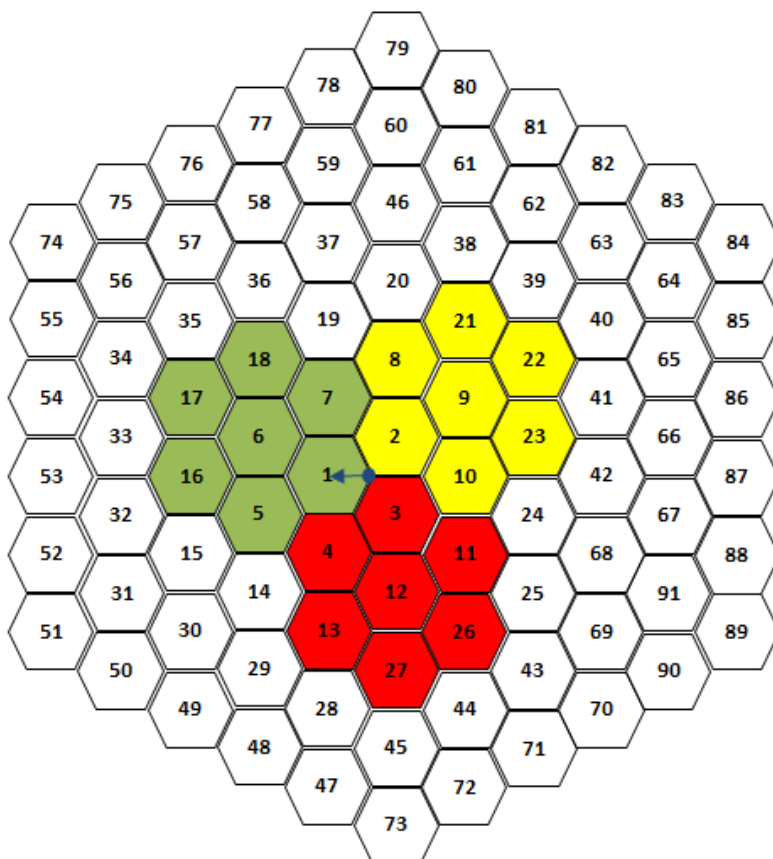


Figure 25. The simulated hexagonal WiB network

The transmitters in the green cluster are assumed to contribute fully to the wanted signal, i.e. with no self-interference, but the guard interval duration is assumed to be zero for the purpose of

spectral efficiency calculation. Because of the low  $C/(N+I)$  operating point for WiB, the effect of inter-symbol interference is expected to be minimal, particularly if a long Equalisation Interval can be assumed.

The yellow and red clusters are treated as the two interferers which can be handled by the Shannon Diamond approach. The transmitters in the white cells are treated as pure unwanted interference.

### 5.1.5. Summary of key hexagonal network results

Figure 26 shows the results for the main studies conducted with hexagonal networks. The overall spectral efficiency, allowing for the re-use factor, for 95% locations, is shown for each network topology. Equal spectral efficiencies on the vertical axis correspond to the same total bit-rate across all services. The horizontal axis shows the power per active UHF channel divided by the re-use factor. Hence capacities achieved at the same horizontal position correspond to networks having the same power usage totalled across all services and frequencies.

The large blue circles represent networks having the same transmitted power (47 dBW) in the active channels. This is assumed to represent the maximum practical power limit that could be radiated in one channel from one transmitter (i.e. although points on the curves to the right of the blue circle may offer greater efficiency, they are assumed not to be practical and should not be considered).

In the case of WiB it has been assumed that the basic signal would need to be more broadband in order to deliver a sufficiently high bit-rate for efficient statistical multiplexing. Given that the WiB efficiency is typically between 1-2 b/s/Hz, it is assumed that three 8 MHz channels would be needed to provide 24-48 Mb/s. This is why the circle for WiB is at about 42dBW and not at 47dBW as might be expected for re-use 1.

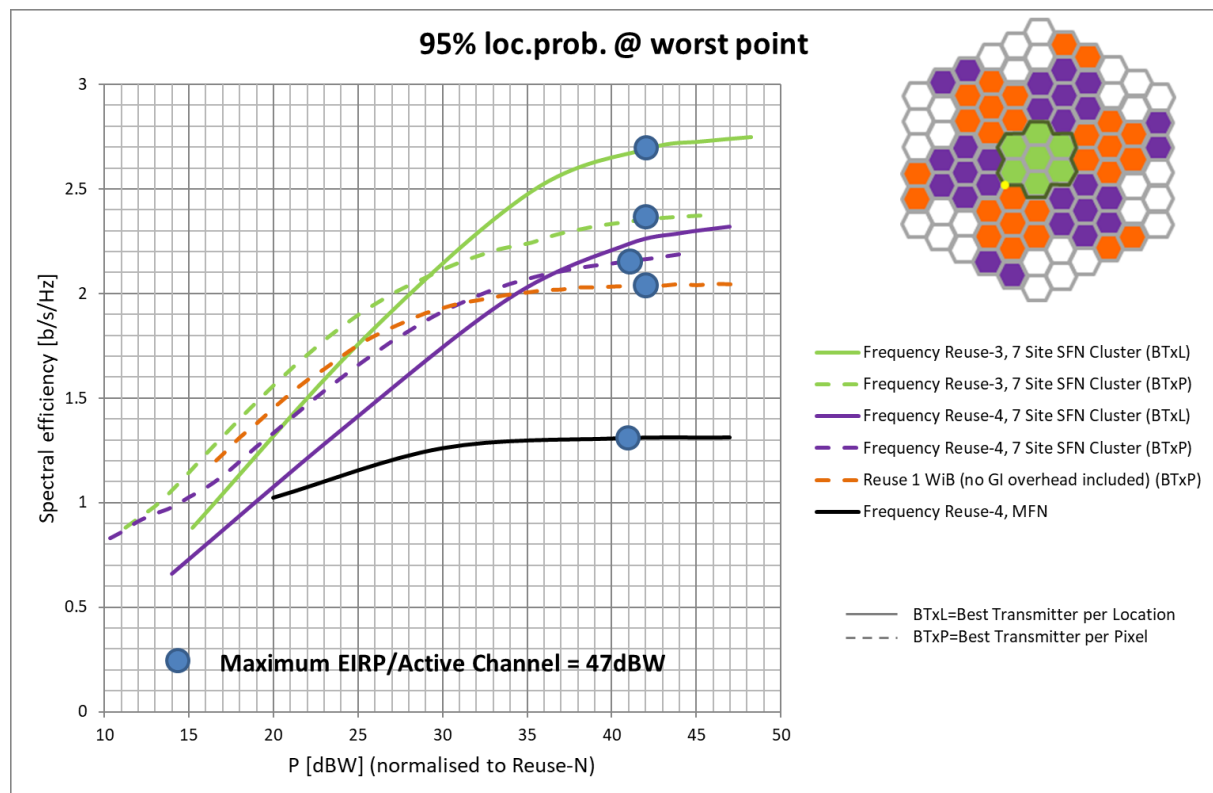


Figure 26. Results for simulations with the main hexagonal networks studied.

The results confirm the basic result that WiB offers greater spectral efficiency at a given total transmit power than an MFN, or alternatively similar capacity at reduced total power.

The results also show that, in the hexagonal case, SFN clusters of size 7 with re-use factors of 3 or 4 could also provide similar or greater increases in capacity. However, it should be noted carefully that we have observed that some of the results from studies conducted with hexagon networks are very different to those from real networks planning studies (see section 5.3), because of realistic regional shapes, geographical differences (mountains, hills, different transmitter heights), and population rather than area coverage targets. These real-world effects will have a significant impact on the interference observed in practice, and perhaps more importantly in many cases the real networks appear to have a combination of limits caused by both interference and noise (i.e. some areas are limited by interference, others by noise) which is in contrast to the hexagon network studies, which appear to be mostly limited by interference alone.

This makes it virtually impossible to take results from the hexagon network studies and assume that they apply more generally to realistic networks, and it would be dangerous to do so. (This is perhaps a particular problem for broadcast-style HPHT networks, and may be a less serious issue for LPLT cellular networks, which haven't been covered by this study).

Nonetheless the hexagon network studies have still proved a very useful tool, as they allow different organisations to compare results and agree common simulation conditions; they allow a variety of system and planning ideas to be tested much more rapidly than with full network simulations; and they allow greater analysis of the underlying mechanisms at work, since the coverage is often dominated by a single 'worst point' where the signal contributions from each source (i.e. wanted/interfering transmitter or group of transmitters) can be studied, reducing the problem to a tractable set of signal levels to be compared.

These results are discussed further in section 6.

## **5.2. Results from hexagon networks with power splitting**

Power Splitting and Interference Cancellation are studied from a practical deployment perspective using hexagonal-based networks and considering ideal reception via Shannon capacity calculation.

### **5.2.1. Network simulation methodology**

Monte-Carlo simulations are employed to estimate the achievable spectral efficiency of the system in a HPHT (High-Power High-Tower) network, as the common network topology employed for terrestrial broadcasting.

The network is modelled as a hexagonal lattice with 60 km inter-site distance and 250 m effective transmitter antenna height with an omni-directional transmitter at the centre of each hexagon. As receiver antenna the ITU BT.419 reference model is used with 11 dBd gain. Cable loss is assumed 4 dB and noise figure 6 dB according to EBU Technical Report 3348 for roof-top reception. Note that these values refer to 8 MHz channels. The ERP is set to 28 kW with a total bandwidth of 224 MHz. This is equivalent to 1 kW ERP per 8 MHz RF channel and a total of 28 RF channels.

The ITU-R P.1546 propagation model is chosen for the land path. Received field strength time availability is assumed 50% for constructive contributions and 1% for interference. Location-dependent fading is added by means of a statistical process modelled as a log-normal random

variable with 0 dB mean and 5.5 dB standard deviation. The receiver location is chosen as the worst point in the network, which corresponds to a hexagon corner. The antenna is pointing towards the nearest transmitter of the wanted SFN cluster.

Each transmitter in the network is assumed to transmit on a frequency reuse-1 basis. The same power pattern distribution is used for all transmitters within an SFN cluster, but adjacent clusters use different power-splitting, which is repeated across different SFN clusters. Real broadcast network implementation, taking into account international frequency co-ordination, typically requires at least reuse-4 to be used on the level of countries (cf. 4-color problem).

A cluster is integrated by a set of transmitter cells which transmit the same content with the same power-splitting. Contributions in the same cluster are assumed to be constructive or destructive as a function of the relationship between the relative delay and the OFDM parameters (i.e. guard interval - GI, equalization interval and OFDM symbol period). In the simulations, different guard interval durations are considered. The equalization interval is considered to extend up to the useful OFDM symbol duration. The OFDM symbol duration is assumed 4 ms as an approximation to the figure currently employed in DTT standards.

The total bandwidth assigned per transmitter (or cluster) is divided up into  $n$  sub-bands. Each one is associated with a different weight which models the power-splitting mechanism. Each sub-band is interfered by signals of different power according to the power-splitting distribution and the applied power splitting reuse, which makes it possible to limit the impact of interference. Note that the actual power splitting reuse and the cluster size play an important role.

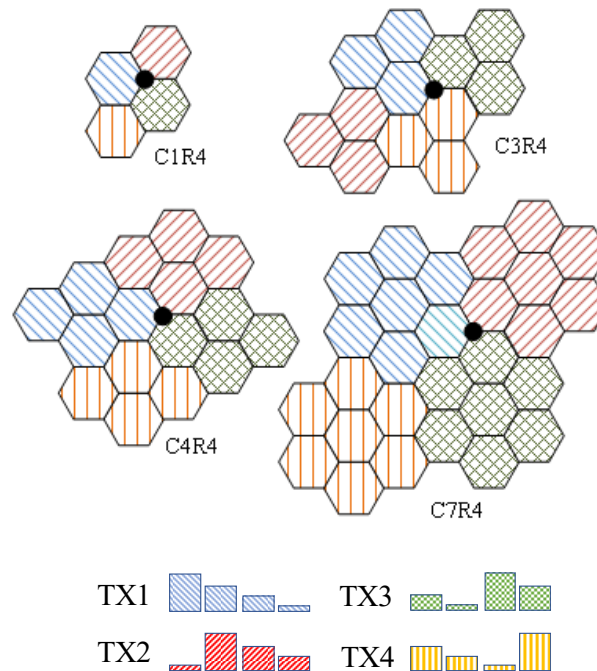


Figure 27. Hexagonal networks for different cluster sizes and reuse-4-based power splitting. The black dot represents the receiver position, which points to the center of the hexagon.

Figure 27 presents four examples of hexagonal networks with cluster sizes 1, 3, 4 and 7 in a power splitting reuse-4 basis. These patterns are replicated to extend the area. A total of 127 transmitters are considered. The effect of the reuse is depicted in the bottom part of the figure. Each transmitter gets assigned the same total power but the weighting per sub-band is cyclically frequency-shifted for each cluster. Note that, on average, the combination of signals per sub-band remains constant.

The achievable rates are calculated according to the received signals and multiple decoding strategies. Finally, the rate is calculated under the broadcasting assumption that all transmitters must provide the same rate. As an example, considering the reception of three signals (S1, S2 and S3) and with S1 being the wanted signal, the rate would be the maximum of:

- S1, while S2 and S3 are regarded as Gaussian noise.
- $1/2$  of the sum rate of either S1 and S3, or S1 and S2 (treating the remaining S2 or S3 as noise).
- $1/3$  of the sum rate of S1 and S2 and S3.

### 5.2.2. Simulation results

Figure 28 shows the rates (in bit/s/Hz) calculated according to the methodology explained above. Different vertical lines are highlighted. Line A corresponds to one of the extreme cases in which the power-splitting is maximum and only one sub-band is active. On the other side, line D corresponds to the case in which all sub-bands are assigned the same power. Intermediate lines B and C are those in which 2 and 3 sub-bands, respectively, are employed with the same power. Power-splitting progressively evolves from one line to another in terms of assigning more power to the adjacent sub-band until the full bandwidth is covered. Each band is assigned a weighting value  $w_i$  which is normalized by the sum of the weighting values of all bands so that total power remains constant. In the calculation shown in this paper for 4 bands,  $w_1$  is set to 10 (with  $w_2, w_3$  and  $w_4$  being 0). From line A to B  $w_2$  increases in one unit until reaching a value of 10 at line B. This means that the normalized weights at B are 0.5, 0.5, 0, 0. The same process is done when assigning more power from B to C and C to D, ending in a distribution of 0.25, 0.25, 0.25, 0.25.

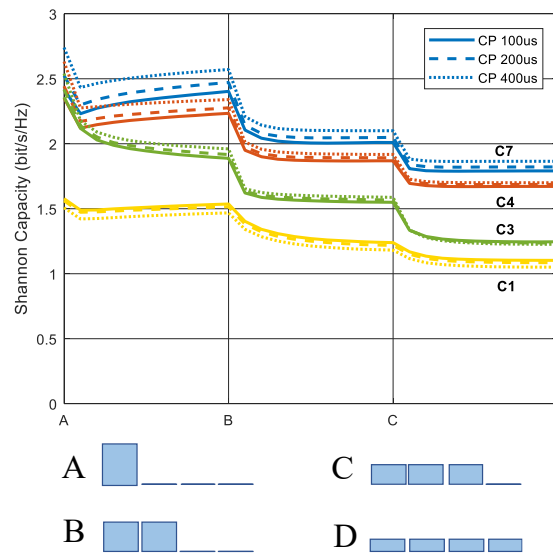


Figure 28. Achievable rates with power-splitting for cluster sizes 1, 3, 4 and 7 with reuse-4-based power splitting.

Four groups of curves are shown per each cluster size from 1 to 7 transmitters. Each line takes into account different GI duration (100, 200 and 400  $\mu$ s), i.e. GI overheads are taken into account. The effects of SFN self-interference can be seen especially with cluster size 7. In case of cluster size 1 the GI is just an overhead penalty.

The network with cluster size 1 and reuse-1 presents the worst performance due to the presence of high interference levels from close transmitters. Interference progressively decreases when increasing cluster size.

From the point of view of power-splitting, the situation in line A suggests that high rates can be obtained when power is confined in orthogonal sub-bands, particularly for large cluster sizes. A drop in capacity can be observed when part of the power is assigned to a new sub-band. The desired rate between the two extreme cases can be fine-tuned by the selection of particular weighting parameters per sub-band.

Power splitting allows for higher spectral efficiency compared to reuse-1 without power splitting. It turns out that by increasing the degree of power splitting the spectral efficiency is progressively increased all the way to pure reuse-4, which – as mentioned above – can be seen as an extreme form of power splitting. When also power saving is taken into account, and also some implementation aspects, there are interesting trade-offs using power splitting that allows both a very good spectral efficiency and a good power saving. Power splitting can therefore be seen as kind of soft reuse, which allows intermediate trade-offs between spectral efficiency and power saving, which are between those at the end-points: pure reuse-1 and pure reuse- $n$  (in this paper with  $n=4$ ).

This kind of network performance behaviour exists with ideal receivers. When introducing real receiver algorithms there are additional advantages by power splitting, since it facilitates how the ideal (full rate region) performance could be approached in a broadcast context. Applying wideband signals with JIDD receiver processing seem to allow very good performance for a wide range of C/I conditions.

The analysis has concentrated on a particular power splitting approach together with reuse-4 since, for real broadcast network implementation reuse-3 is probably unsuitable, taking into account international frequency co-ordination, which typically requires at least reuse-4 to be used on the level of countries (cf. 4-color problem).

### **5.3. Results from UKPM studies**

Studies of the potential performance of WiB in the UK were carried out using the UK Planning Model [18], an extremely detailed model jointly developed by four UK organisations and used for planning DVB services in the UK. The model takes into account topography, clutter and propagation and has given results that compare well with measurements in the field.

The model was used to compare a Multiple Frequency Network (MFN) as traditionally used in the UK with a WiB network that could be deployed using the same transmitter sites.

#### **5.3.1. Planning parameters for reference MFN**

The reference network used for the study is the UK DVB-T2 network that will be in operation once the 700MHz clearance process is complete. This has approximately 1100 transmitters, comprising 81

main stations and over 1000 relays. The main stations use horizontal polarisation and the relays use vertical polarisation. The network uses 28 8MHz UHF channels (21-48).

The radiation patterns for the transmitters are based on the real transmit antennas; in the case of the main stations, these have been verified by helicopter measurements. The antenna heights and transmit powers are the same as in the planned network.

The time variation was modelled using the 50% time values for the wanted signals and the 1% time values for interfering signals. The time correlation between transmitters was set to 100%.

Location variation was modelled using a lognormal distribution with a standard deviation of 5.5dB this is the value usually used for 100m x 100m pixels as used in the UKPM (see section 5.3). Zero site-to-site correlation is assumed.

The best transmitter per pixel method (section 4.3.3.2.1) has been used to calculate the coverage. A pixel is deemed to be served if the coverage criteria of 70% of locations or higher is achieved. Then, 100% of the population in each of the served pixels is added up and used to calculate a percentage of the UK's total population that is covered.

The target population coverage used is 98.44%; the question of population coverage is discussed further in section 5.3.6.

### **5.3.2. Planning parameters for WiB network**

The parameters for the WiB network are the same as for the MFN (section 5.3.1) except for the following differences:

Most importantly, all the transmitters in the network operate on the same frequency, and all the transmitters in a given region operate in an SFN. The regions are areas that, in the MFN plan, receive different content on some services, and are shown in Figure 29.



Figure 29. Map of the UK where the transmitters in a region – marked in bold lines – form an SFN and transmit different content i.e. different editorial region.

Antenna patterns from the relevant transmitters in continental Europe and Ireland are omnidirectional in the WiB case. This was done on the basis that the directional radiation patterns currently used (and used in the MFN results) would not be necessary in a WiB scenario owing to the increased interference tolerance. Furthermore, it is assumed that interference from these stations can be cancelled or handled by the receiver in the same way as interference from within the UK. Note that this would require co-ordination between countries, whose networks would need to be synchronised in time and frequency and to use complementary pilot patterns where applicable.

In the reference condition, each transmitter is operated at the same power as the MFN, and in this case the network turns out to be heavily interference limited. There is therefore scope to reduce the



transmitter power significantly, and this possibility is one of the parameters explored in the study (see below).

### **5.3.3. OFDM parameters**

The study assumed the use of a 32K FFT mode, hence an active symbol period of 3584 $\mu$ s. The guard interval (GI) and equalisation interval (EI) parameters [19] are both needed for the UKPM, which calculates the wanted and unwanted contributions arising from inter-symbol and inter-carrier interference. The guard interval is also an overhead which needs to be taken into account in calculating the spectral efficiency.

The effect of both parameters, GI and EI, was explored in the study (see below).

### **5.3.4. Channel model**

The UK network is planned for rooftop reception and hence the Rice channel with K=10 was adopted as the most appropriate channel model.

### **5.3.5. Spectral efficiency calculations for WiB.**

For WiB, the spectral efficiency available at each point in the coverage area was calculated for a range of receiver techniques and theoretical limits: the Shannon Pentagon capacity (section 3.2.2), the Shannon Diamond (section 3.2.5), Joint demapping (section 3.3.2), Gaussian demapping (section 3.3.3) and Hard-SIC (section 3.3.4), based on the predicted wanted and interfering signal strengths and thermal noise levels for that point, according to the formulas derived in the respective sections.

Since it is assumed that WiB would be used in all available UHF channels, the spectral efficiency for a used channel is equal to the spectral efficiency for the TV band overall.

### **5.3.6. Spectral efficiency for the MFN**

For the MFN case, it is more difficult to obtain a single value for overall spectral efficiency that can be compared with the WiB scenario.

In principle, the total number of UHF channels could be divided by the number of multiplexes to obtain the effective frequency re-use factor. The spectral efficiency in a used channel could then be divided by the re-use factor to obtain the overall value.

The main complication is that the UK MFN plan delivers six multiplexes that do not have equal population coverage. The three “Public Service” multiplexes, PSB1-3, serve 98.44% of the population, hence its use as a target (section 5.3.1). The other three “commercial” multiplexes, COM4-6, only cover around 90% of the population. As a result, different households receive a different number of multiplexes and hence total bit-rate. Consequently, it is not obvious what value should be used for the number of multiplexes in calculating the overall spectral efficiency.

Clearly the appropriate number is more than 3 but less than 6. In the study, values of 4 and 5 were used as “pessimistic” and “optimistic” figures for the number of multiplexes, giving effective re-use factors of 6.75 and 5.4 respectively.

The second issue is that calculations of the spectral efficiency of the MFN based on the current plan would include additional DVB-T2 overheads, real FEC code performance and a significant implementation margin. It would not be fair to compare these practical values with the values for

WiB based on theoretical limits. On the other hand, it would be difficult to apply practical margins to the WiB case since the performance of any practical WiB system or implementation is currently unknown. It was therefore decided to use theoretical limits for the capacity of the MFN: such limits were not expected to be practically achievable but could be fairly compared with the WiB results.

Later in the WiB study mission, attempts were made to allow for implementation losses in WiB, in particular since the impact of a given loss in dB is greater at lower C/N; see section 6.1.

The DVB-T2 mode used in the UK uses 256-QAM rate 2/3, requiring about 18dB C/N [7], but the UKPM allows a 2dB margin and considers a pixel covered if 70% of locations receive 20dB or more C/(N+I).

In the study, two values of basic spectral efficiency value were used: the BICM (section 3.2.6) and Unconstrained Shannon capacity (section 3.2.1) at this 20dB point. The former is a fairer comparison with WiB results based on BICM limits (Gaussian Approximation, Joint Demapping and Hard-SIC), whilst the latter is a fairer comparison with the Shannon pentagon and diamond limits.

Figure 30 shows the two capacity curves: the BICM limit for 256-QAM is 6.10bps/Hz and the unconstrained Shannon Limit is 6.53bps/Hz. By comparison, the practical UK DVB-T2 mode achieves just over 5bps/Hz.

Applying the “optimistic” and “pessimistic” re-use factors results in overall spectral efficiencies of 1.12bps/Hz and 0.90bps/Hz respectively for BICM, and 1.20bps/Hz and 0.96bps/Hz respectively for Shannon. These values are used as appropriate for comparison in the subsequent results sections.

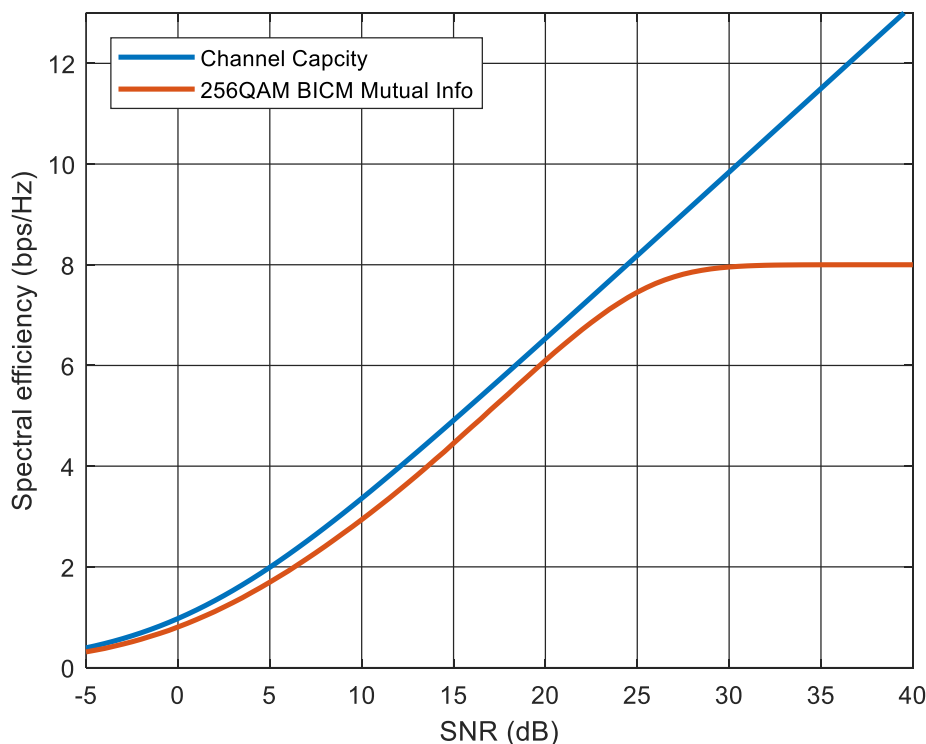


Figure 30. Unconstrained Shannon channel capacity and BICM mutual information for a 256QAM constellation vs. SNR in dB in an i.i.d. Rice ( $K=10$ ) channel model.

### 5.3.7. Power reduction

In the WiB results presented here, the power of each transmitter in each 8MHz channel is 17dB lower than for the MFN. However, since the WiB system uses all the UHF channels from every site, the overall power reduction is less.

In a further complication, in the MFN, not all of the multiplexes are transmitted from each transmitter site; furthermore the “COM” multiplexes are often transmitted at lower powers to the “PSB” multiplexes from the same site. However, the total power of the MFN can be calculated by adding up all the transmit powers, and the total WiB transmit power can be calculated by multiplying the total power in one channel by the number of UHF channels, 28. When this is done, it turns out that the WiB network would be operating at approximately 10% of the total power of the MFN, in line with the 90% power saving outlined in section 2.1.

Early results from the UKPM showed that a power reduction per channel of 17dB gave only a very small penalty in achievable capacity compared to a 0dB reduction (see Figure 31).

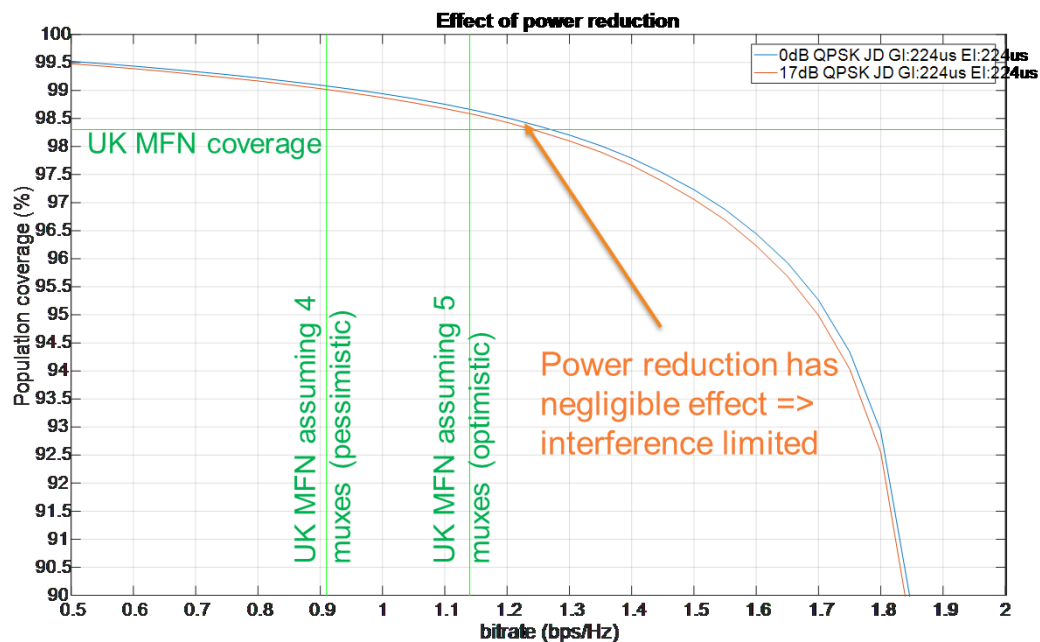


Figure 31. Effect of power reduction on the population coverage using UKPM for QPSK constellation, JD demapper in an i.i.d. Rice channel.

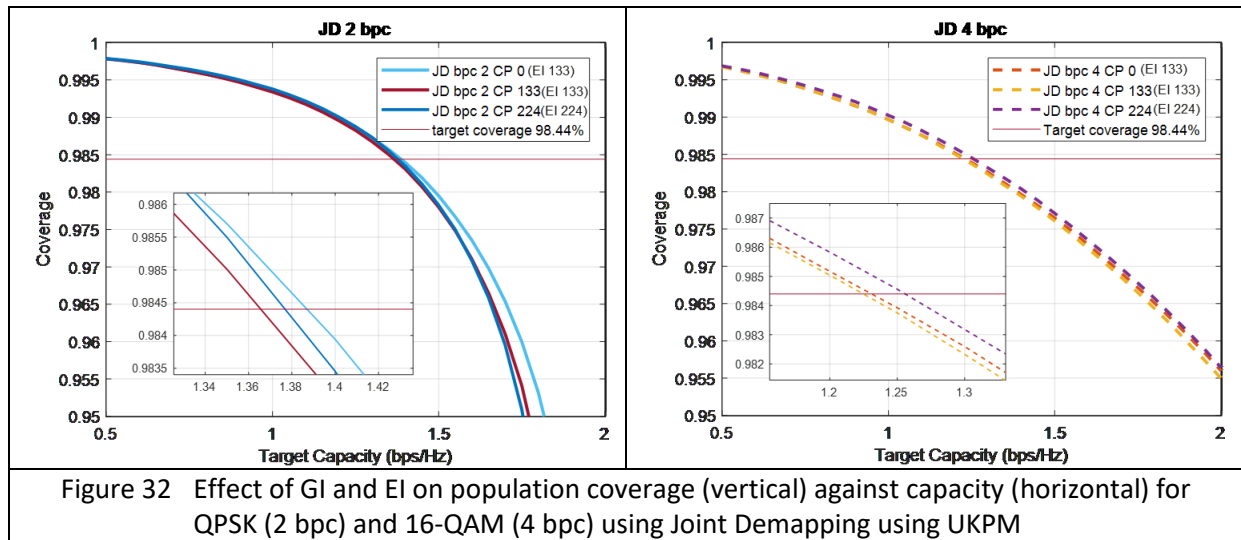
This suggests that the network was interference limited. However, those results only simulated Joint Demapping. The later results presented below, for the Shannon pentagon and diamond, give significantly higher capacities. It is possible that, at these higher capacities, the results are somewhat noise limited and that a moderate increase in transmitter power (i.e. a lesser reduction in total power) might increase the capacity. Unfortunately, there was not time to perform the necessary simulations to investigate this possibility.

### 5.3.8. Results: GI and EI

Figure 32 (left) shows the population coverage (vertical) against capacity (horizontal) for QPSK (2 bpc) using Joint Demapping, for three different Guard Interval durations. In each case, the

Equalisation Interval (EI) is equal to the Guard Interval except for the zero GI case where it is set to 133 $\mu$ s. Figure 32 (right) shows the corresponding results for 16-QAM (4bpc). At the target population coverage, the effect of GI on capacity is minimal, because increasing the GI/EI decreases self-interference but increases overhead and the two effects largely cancel out. Zero guard interval is slightly better for QPSK but the longer 224 $\mu$ s GI is best for 16-QAM.

A similar conclusion – that the GI has a very limited effect – is obtained for the other receiver approaches and theoretical limits.



### 5.3.9. Results: Constellation order

Figure 33 shows the effect of constellation order for three receiver approaches. At the target population coverage, QPSK (the solid lines) provides better capacity than 16-QAM (dashed lines) for all three receiver approaches.

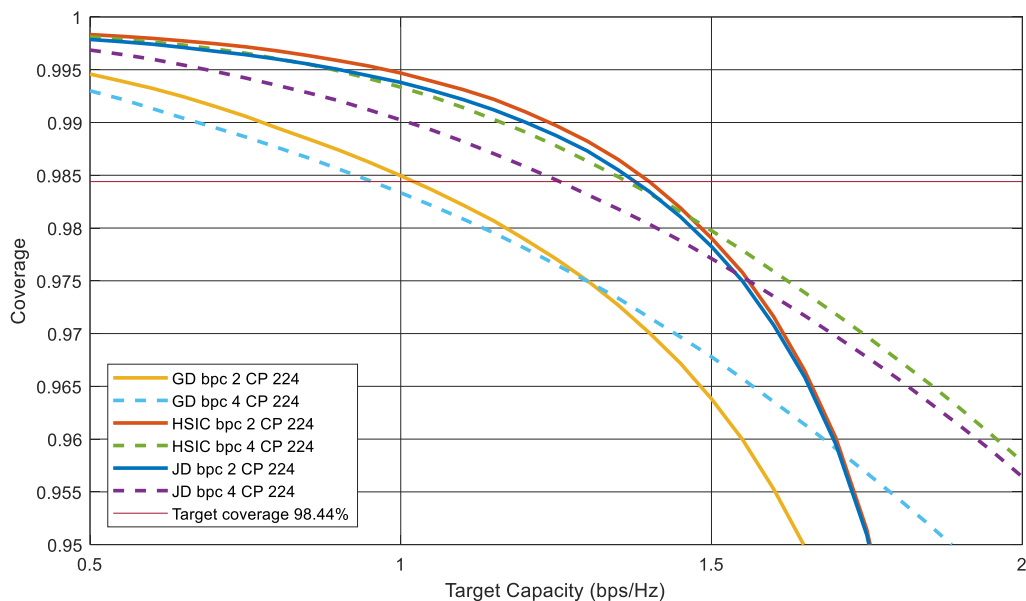


Figure 33. Effect of constellation order for three receiver approaches on population coverage (vertical) against capacity (horizontal) using UKPM.

### 5.3.10. Results: Comparison of receiver approaches

Figure 34 shows the results for all of the receiver approaches and the theoretical limits simulated, for QPSK, which was established in section 5.3.9 to be the best choice at the target population coverage. The dashed vertical lines show the optimistic and pessimistic spectral efficiencies for the UK MFN, for both BICM and Unconstrained Shannon limits. The order is as expected: GD falls around the mid-point of the UK values, whilst JD gives a significant improvement. Hard SIC (HSIC) only marginally improves the coverage compared to JD, suggesting that there are few locations that fall in the beneficial region given in section 3.3.5.

The Shannon Pentagon gives a valuable improvement over Hard-SIC, whilst the Shannon Diamond limit gives a small but significant further increase.

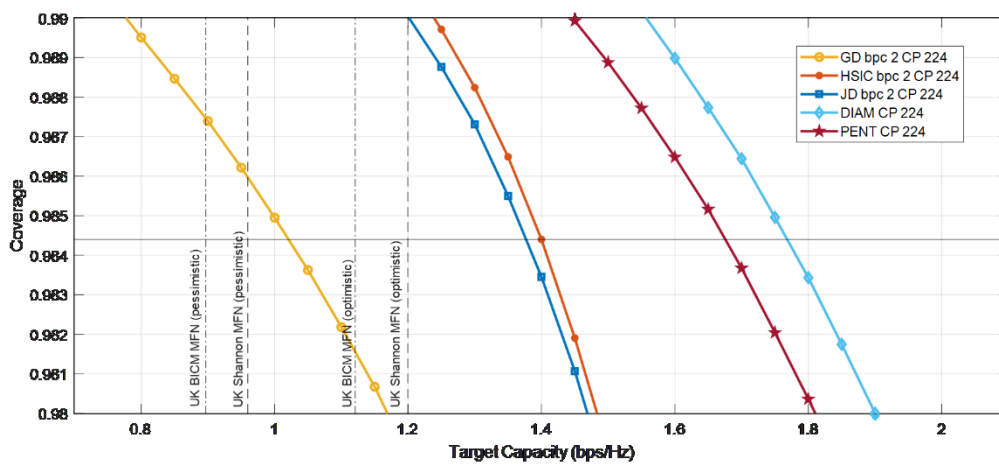


Figure 34: Coverage results for all of the receiver approaches and the theoretical limits for QPSK using UKPM. For comparison dashed vertical lines show the optimistic and pessimistic spectral efficiencies for the UK MFN, for both BICM and Unconstrained Shannon limits.

### 5.3.11. Results: Summary of WiB gains

The table below summarises the unconstrained Shannon performance. The results for Shannon Capacity in the MFN are compared with the results for Shannon Pentagon and Shannon Diamond in the WiB network. Both pessimistic and optimistic values for the MFN are considered.

	MFN Shannon	Pentagon increase (AWGN)	Diamond Increase
Pessimistic MFN	0.96 bps/Hz	75%	84%
Optimistic MFN	1.20 bps/Hz	40%	47%

The potential increase in spectral efficiency is impressive, even compared to the optimistic interpretation of the efficiency of the UK MFN. However, this would require new network planning and new receivers capable of optimally handling one or two interferers for the Pentagon and Diamond limits respectively.

The table below shows the increase in capacity possible for the practical receiver approaches in WiB assuming QPSK constellations. As a baseline, the BICM performance of the MFN is used in this case, since the receiver techniques considered are also based on the BICM limits.

It was not possible to obtain results for the UKPM with Power Splitting and JIDD (see section 3.3.6), which might be the best realistic practical approach. However, the Shannon Pentagon and Diamond results represent an upper bound on the performance of this approach (for one or two interferers respectively) and are shown for comparison.

MFN BICM		Increase in capacity				
		GD	JD	Hard-SIC	Pentagon	Diamond
Pessimistic MFN	0.90bps/Hz	14%	54%	56%	87%	97%
Optimistic MFN	1.12bps/Hz	-8.9%	23%	25%	50%	58%

The results show that WiB offers significant gains for both idealised and practical techniques compared to the UK MFN. However, the MFN is not necessarily optimal from a pure capacity viewpoint, and other network approaches could also give improvements. This will be discussed in more detail in section 6.

#### 5.4. The Italian case

For Italy it is assumed that the international reuse-factor is about 2, due to the interference screening effect of the Alps and of the surrounding Mediterranean sea. This should be applied after 700MHz band clearance by 30/6/2022, as resulting from international coordination, that have globally assigned to Italy 14 out of the 28 channels in UHF band. Current hypothesis under study considers 10 national MUXes and 4 local ones allocated to Italy out of the 28 available in UHF. Figure 35 shows two examples for the national MUXes, while Figure 36 give an example of local MUX allocation allocation (for a full representation of all the MUXes see [20]).

For national MUXes:

- 3 networks are allocated a single frequency throughout the country, possibly with some auxiliary frequencies coordinated with neighbouring countries;
- 6 networks are allocated 2 frequencies throughout the country, possibly with some auxiliary frequencies coordinated with neighbouring countries;
- 1 network is allocated a single frequency throughout the country, possibly with some auxiliary frequencies coordinated with neighbouring countries.

For local MUXes, the coverage is based on technical areas rather than administrative areas, with possibility to separate the technical areas in smaller areas, based on international coordination. In addition, a regional MUX is available in VHF. The following only takes into account UHF band.

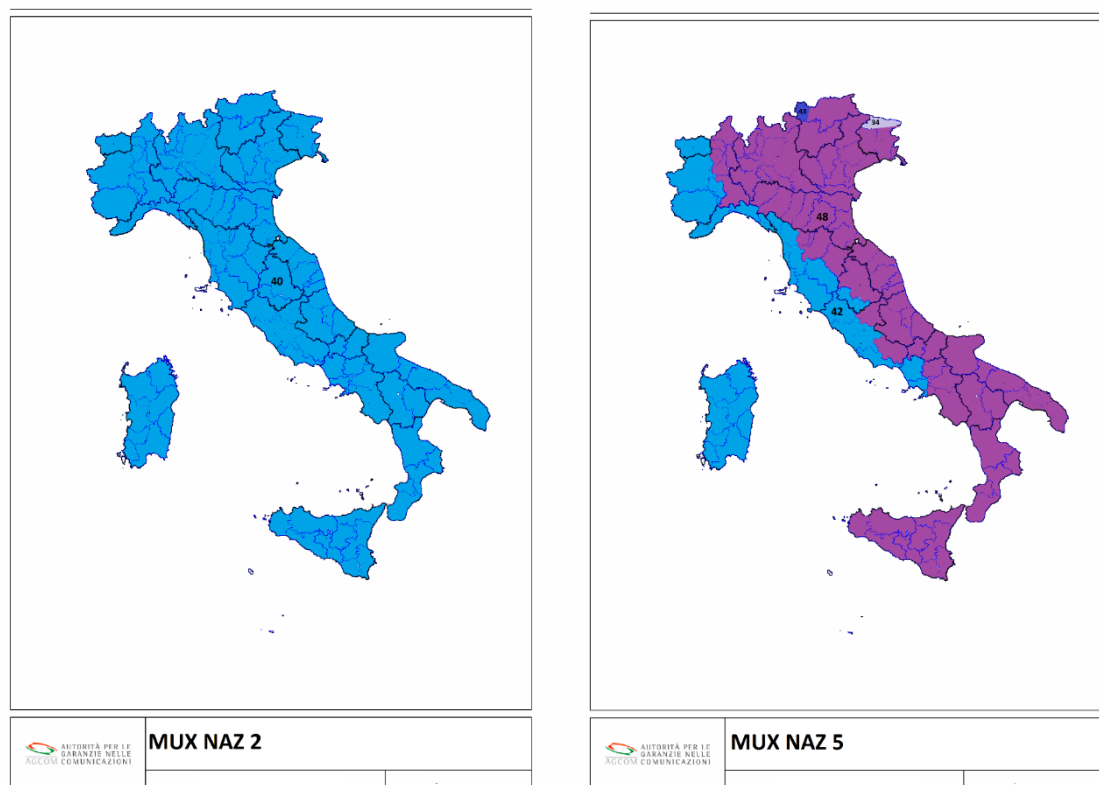


Figure 35 Two examples for the national MUXes frequency allocation

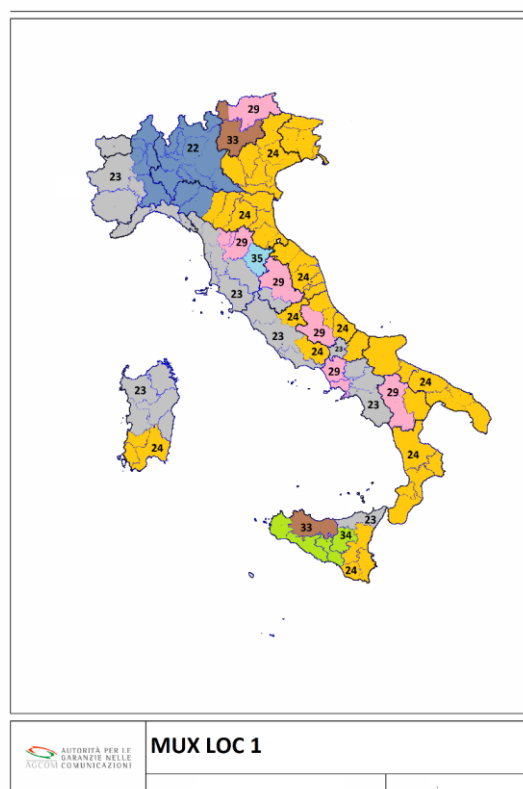


Figure 36. Example local MUX frequency allocation

#### 5.4.1. Reuse-2 planning for national services

To estimate the achievable capacity in Italy for a national SFN configuration, it is assumed that the same coverage of current national SFNs in Italy is achieved, i.e. a SNIR of about 20dB guaranteed for the 99% of the population. This represents the required SNIR for DVB-T2 and 256QAM2/3, GI=448us, PP4, having a channel capacity of 33.3 Mbit/s, and a corresponding spectral efficiency of 4.2 bit/s/Hz per channel. Having a reuse factor of 2, this would result in a effective spectral efficiency of 2.1 bit/s/Hz.

If instead the Shannon capacity is calculated as achievable at 20dB SNIR, this corresponds to 6.5 bit/s/Hz, becoming 3.2 bit/s/Hz for a frequency reuse factor of 2.

#### 5.4.2. Reuse-4 planning for regional services

Figure 37 shows possible colouring of Italy for reuse-3 and 4 SFN regional clusters.

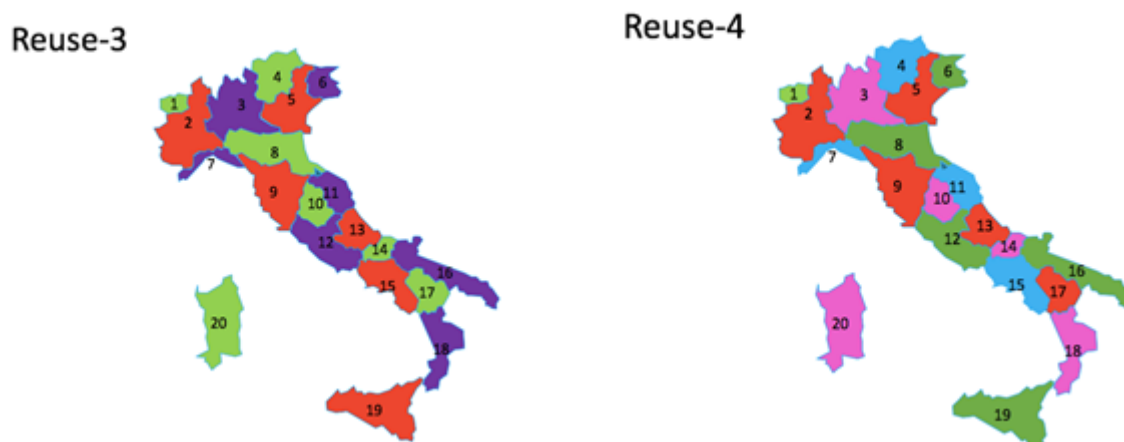


Figure 37: Example colours for Italy and reuse-3 / reuse-4 regional SFN clusters

It is clear that, with reuse-3 and conventional systems, the irregular region dimension and shape produce sometimes high interference levels between “same-colour/nearby” regions (e.g. for Italy regions 3-7, 8-10 and 11-12), which could limit the overall capacity of the national plan. Such critical situations can be improved by assigning opposite polarizations to critical “same-colour/nearby” areas.

Reuse-4 maps allow better area separation for reduced interference (and more flexibility to control interference in other critical situations).



According to the same assumptions as for the national services, the Shannon spectral efficiency for frequency reuse 4 is 1.6 bit/s/Hz. Taking into account of a frequency reuse 2 for international coordination, the resulting spectral efficiency for regional services is 0.9 bit/s/Hz.

### **5.4.3. Shannon capacity for Italy**

Taking into account of the allocation of all the frequency resources in UHF to nation-wide SFN, assuming that the regional MUX will be implemented in VHF, the Shannon spectral efficiency for Italy could be estimated as follows:

$$\eta_S = 3.2 \text{ bit/s/Hz}$$

In the case of real DVB-T2 system this reduces to:

$$\eta_{T2} = 2.1 \text{ bit/s/Hz}$$

This should be compared to the capacity achievable with WiB reuse-1. Assuming the same result as for the UK case,  $\eta_{SW} = 1.7 \text{ bit/s/Hz}$ , it comes out that under the given hypothesis the adoption of WiB instead of reuse-2 planning with international coordination would penalise achievable capacity in Italy of about 47%.

If instead it is assumed that about 70% of frequency resources are allocated to nation-wide SFN, and the remaining 30% for regional- SFN, the Shannon spectral efficiency for Italy could be estimated as follows:

$$\eta_S = 0.7 \cdot 3.2 + 0.3 \cdot 0.8 = 2.5 \text{ bit/s/Hz}$$

In the case of real DVB-T2 system this reduces to:

$$\eta_{T2} = 0.7 \cdot 2.1 + 0.3 \cdot 0.5 = 1.6 \text{ bit/s/Hz}$$

In this case the adoption of WiB instead of conventional reuse-N planning with international coordination would penalise achievable capacity in Italy of about 32%.

## **6. Discussion of results**

The previous section presented the results of studies for both WiB and traditional approaches to network planning. This section draws comparisons between the results, and attempts further interpretation of them. The conclusions from this analysis are presented in the next section.

From the results of the hexagon network studies, and based on a comparison of Shannon capacity in a Gaussian channel, WiB (with regional clusters of 7 cells operating in an SFN) shows a significant potential gain over traditional MFN planning with re-use 4 (e.g. around 2.2b/s/Hz for WiB vs. 1.3b/s/Hz for MFN). It should also be noted that MFN planning usually requires a higher re-use factor (e.g. 5-7), which would further reduce its efficiency, and hence increase the relative gain of WiB.

However, it can also be seen that if the comparison is made between WiB and regional SFNs also planned with clusters of 7 cells, the regional SFN approach shows a similar or greater increase in capacity.

However, as mentioned previously, conclusions taken from hexagon networks are very different to the conclusions from real networks, because of regional shapes, geographical differences (mountains, hills, different transmitter heights), and population-based rather than area coverage targets. Furthermore, we need to allow for both noise and interference limits, making comparisons even more difficult.

The results from the UK planning model based studies are full detailed planning studies, but of course only give the answer for one country, and therefore can't necessarily be generally applied to other countries.

The UK planning model studies show that a Shannon capacity of 1.76b/s/Hz would be achieved for WiB, using a Rice channel, with the transmitters operating at -17dB compared to the current network, and operating as a regional SFN. In comparison the current MFN has a Shannon capacity of 0.96-1.20b/s/Hz, again for the Rice channel. Whilst this represents a significant apparent gain, further consideration is needed, as discussed in the next section.

Conversely, the results from section 5.4, based on a study of the proposed Italian situation by 2022, suggest that the introduction of WiB would introduce a loss of 32-47% in Italy.

### **6.1. Interpretation of results**

The figures presented above give the raw comparisons of Shannon capacity from the various scenarios studied. In principle, comparing Shannon capacity for different network structures would allow a simple gain figure to be calculated for one structure compared to another, that would be quite similar to the gain achieved with practical implementations, assuming there would be similar losses for real implementations in any two cases being compared. Unfortunately, there are two factors that mean a different approach is needed:

- 1) The power splitting and JIDD approach described in sections 3.3.6 and 3.3.7 is significantly different from a traditional DTT receiver approach, and may have further implementation losses associated with it (although it may not yet be the optimal strategy for obtaining the best performance from such a system)
- 2) Much more significantly, but rather less obviously, the effects of implementation losses are much greater at the lower operating points associated with WiB than they are for the much higher operating points used in traditional DTT networks.

To estimate these implementation effects, the following approach was adopted. We assumed that the typical loss for a real FEC code in a traditional DTT network is around 2dB, whereas we use the implementation figure of 1.3dB for JIDD with real FEC codes from section 3.3.7.1. We then apply these figures to the appropriate Shannon operating points, which are assumed to be approximately 20dB and 5dB respectively. We calculate the reduction in capacity by taking the Shannon capacity at

the desired operating point<sup>5</sup>, and comparing with the Shannon capacity at the operating point reduced by the implementation margin, as shown in the table below.

	<b>Traditional DTT</b>	<b>WiB</b>
Operating point	20 dB	5 dB
Shannon capacity	6.66b/s/Hz	2.06 b/s/Hz
Implementation loss	2 dB	1.3 dB
Capacity at operating point reduced by implementation loss	6.0 b/s/Hz	1.74 b/s/Hz
Capacity implementation factor	90% (i.e. 10% loss)	85% (i.e. 15% loss)

We can then apply these implementation factors to the raw results from above to obtain:

	<b>UK MFN</b>		<b>WiB</b>
	Pessimistic	Optimistic	
Raw capacity (Rice channel)	0.96 b/s/Hz	1.20 b/s/Hz	1.76 b/s/Hz
Net capacity allowing for implementation	0.87 b/s/Hz	1.08 b/s/Hz	1.49 b/s/Hz
Gain for WiB c.f. pessimistic MFN			72%
Gain for WiB c.f. optimistic MFN			38%

Recognising that the use of regional SFNs in the UK might provide some additional benefit over the use of MFNs, estimated at around 10%, the above range of potential gains for WiB would be reduced if compared to a starting point of regional SFNs, bringing the range of gains for WiB in the UK case down to 28-62%. However, it should also be noted that we have so far not studied detailed implementation approaches for WiB, which could easily reveal additional implementation losses, further reducing these gains.

These results are based solely on the UK case, which are the only detailed planning studies with real networks that have been done with WiB, but would need to be further checked with detailed planning studies in other countries to verify their general applicability.

## **6.2. Comparison with theoretical network scenarios**

Extending the arguments from above, it might be expected that further gains could be obtained for traditional planning using a national SFN (see for example [21]). To test this idea, it was assumed that the 28 UHF channels remaining following completion of the release of 700Mz spectrum could be used to provide 5 national multiplexes and 1 regional multiplex<sup>6</sup>. Two planning approaches were

<sup>5</sup> We have used the values based on a Gaussian channel, whereas strictly a Rice channel would be more appropriate, but the effect on the overall calculation would be expected to be minimal

<sup>6</sup> It is not certain that such a configuration could easily be coordinated amongst all neighbouring countries, but it had been assumed as a working hypothesis to allow at least some comparison to be made

considered, one typical for the UK, assuming a system C/N+I of 20dB, giving a Shannon capacity in a Rice channel of 6.53 b/s/Hz, and a second assuming a higher capacity of 7.5 b/s/Hz, based on the results from the hexagon networks with re-use 3, but with the power reduced by 7dB. The results are given in the table below.

	<b>Approach 1</b>		<b>Approach 2</b>	
Theoretical capacity per channel	52.24 Mb/s		60 Mb/s	
	National SFN	Regional SFN	National SFN	Regional SFN
Guard interval	1/8	1/16	1/8	1/16
Theoretical capacity per channel allowing for guard interval	46.44 Mb/s	49.17 Mb/s	53.33 Mb/s	56.47 Mb/s
Multiplexes	5	1	5	1
Total theoretical capacity	281 Mb/s		323 Mb/s	
Net capacity allowing for implementation	253 Mb/s		291 Mb/s	
Overall spectral efficiency allowing for 28 channels of 8MHz	1.13 b/s/Hz		1.30 b/s/Hz	
Gain for WiB compared to theoretical network scenario	32%		15%	

It should be noted that, as mentioned above for Italy, in specific cases (e.g. very large countries or countries separated from neighbouring countries by mountains or large areas of sea), a more efficient SFN planning approach may be possible, and so the WiB gain would be significantly lower than for a conventional system using SFN planning. Equally however, note that the comparison with WiB is for the WiB system based on a UK regional SFN plan, and increased efficiency might also be observed if it too were planned on a national basis, but that work has not been carried out.

## **7. Additional supporting features**

This section describes some additional features and technologies studied by the group, in some cases as they would be needed to support the implementation of WiB, and in others as extensions the basic principles.

### **7.1. Distributed pilots**

For all interference cancellation approaches the receiver needs to estimate the channel of each signal being included in the interference cancellation process. This normally means that each signal needs to have its own dedicated pilot pattern, which is orthogonal to all other signals. One way of achieving this is to let each pilot cell position in one signal correspond to a null cell, i.e. an OFDM cell with no transmitted energy, in all other signals. The total number of cells that need to be a pilot cell or a null cell is therefore proportional to the number of signals being processed. With e.g. a hexagonal network and a receiver processing three received signals – one wanted and two potentially interfering – the overall pilot density needs to be three times higher than if no interference cancellation is supported.

To support SFN operation, traditionally (e.g. DVB-T/T2) a relatively dense pilot pattern is used to support the long delay differences that may occur in an SFN. The required pilot density then depends e.g. on the size of the SFN, so a larger SFN normally requires a higher pilot density, irrespective of the number of transmitters within the SFN. DVB-T2 supports 7-TX SFN clusters with ISD=80 km, using the PP2 pilot pattern which has a density of 1:12 ( $D_x=6$ ,  $D_y=2$ ). To support interference cancellation with two adjacent SFN clusters of the same type, would then require a three times higher pilot/null cell density, i.e. 1:4. For a given SFN cluster the actually-used pilots would still only require a density of 1:12, but with the necessary null cells the overall density for pilots and null cells would be 1:4, which is quite large (overhead factor 0.75), but not impossible.

One approach, which may significantly reduce the pilot overhead, and which also has a number of other interesting advantages, is something called “Distributed pilots”, originally proposed by Alessio Filippi (Philips) in the DVB-T2 standardisation [22]. Rather than having a single, dense, pilot pattern for all transmitters in the SFN, there is instead, for each transmitter, a dedicated sparse pilot pattern, which is orthogonal to the transmitted pilots of all other transmitter signals in the same and adjacent SFNs. The receiver can then perform channel estimation of each received transmitter signal, independently of the other received signals, from both the wanted SFN and the unwanted, interfering, SFNs.

With the individual channel estimates the receiver can then assemble a “global” channel estimate, for each SFN, by adding together the individual impulse responses, with appropriate relative delays between these included. The received signals must contain reference information that makes it possible for the receiver to estimate these (presumably quasi-fixed) relative delays.

Assuming natural echoes are restricted to be within e.g. 15  $\mu$ s, the required overall pilot density can be significantly reduced using distributed pilots.

#### Example:

We assume

- Symbol time  $T_u=3584 \mu$ s (same as for the DVB-T2 32K mode)
- Support for channel estimation of three adjacent 7-TX SFN clusters ( $3 \times 7 = 21$  TXs in total)
- Natural echoes limited to 15-16  $\mu$ s (including interpolation filter margins)
- Required pilot density per TX signal: 1:400 ( $D_x=200$ ,  $D_y=2$ )
- Null cells in OFDM cell positions of other TX’s pilots (in wanted and adjacent interfering SFNs)

Pilots and null pilot positions would then occupy a proportion of  $21/400 = 5.25\%$  of all OFDM cells. The corresponding overhead factor becomes  $(400-21)/400 \approx 0.95$ . In addition, further overhead is needed for estimation of relative delays, which is likely to be handled by appropriate reference information in a preamble.

Since the required pilot density of each TX signal would be very low (e.g. 1:400, see example above) this could allow a very significant pilot boosting, which in turn would allow a very significant noise reduction of received pilots. It should be noted that since null cells do not carry any energy it is only the “active” pilot density that is of relevance for the boosting trade-off. Since the null cell positions do not carry any energy this energy can instead be spent on the rest of the signal (for a given total

power). The resulting channel estimate is expected to become potentially much more noise-free than is normally possible in DVB-T/T2.

MISO transmission is known to allow significant performance gains in SFNs, as long as two received signals have different MISO type. MISO provides however no gain when the MISO type is the same, which normally happens in SFNs with more than two TXs. In DVB-T2 MISO also requires twice the pilot overhead to that in SISO.

Assuming distributed pilots are instead used, and all TXs use their dedicated pilot pattern, one could get the benefit of MISO for free, i.e. unlike DVB-T2 the use of MISO would not imply an increase of pilot overhead. A new standard could also employ a further-developed use of MISO – *dynamic MISO* (see TM-WiB0067), which may offer advantages compared to the way MISO is specified for DVB-T2.

The attractive thing with MISO is that it may offer Gaussian (AWGN) performance in SFN reception cases where two signals are being received at about the same level. In the “classical” non-MISO case this causes strong frequency fading, e.g. a 0 dB echo, with associated C/N degradation. The drawback is that this nice behaviour does not apply generally. With MISO, transmitters may be assigned to be of one of two types (e.g. type A and type B). The gain only exists when signals of different types are received (i.e. A/B, but not A/A or B/B) – when they have the same type there is no gain and performance is like non-MISO. This means that depending on location in the network the receiver may experience full MISO gain or no gain, which is an undesirable behaviour. It would be much more desirable to have the *same* type of performance for *any pair* of received transmitter signals. This target is addressed by TM-WiB0067 (Teracom), in which a developed variant of MISO, called Dynamic MISO (D-MISO) is proposed.

With Dynamic MISO the allocation of MISO type would not be done on a per-transmitter basis, but with a finer granularity. This would allow each transmitter to play the role of both type A and type B, with the type changing with frequency and/or time, but in different ways relative to other transmitters. The effect of this would be that for 0 dB reception situation, with any pair of transmitters, it would always be the case that 2/3<sup>rd</sup> of the bandwidth (or time) would fully benefit from the nice A/B behaviour, whereas 1/3<sup>rd</sup> would experience the classical zero-gain behaviour, i.e. with some C/N degradation relative AWGN performance (this is the way all existing DTT networks behave). The net effect is that the overall performance is significantly improved in such 0 dB situations compared to the classical case and – unlike T2-MISO - it is also independent of the particular TX combination. The estimated gain for WiB is theoretically estimated to be between 1.1 and 1.6 dB for 0 dB reception situations.

Finally, distributed pilots offer a potentially very important gain in that they could be designed to allow channel estimation almost independently of the size of the SFN, as long as received pilots are orthogonal. This could allow the performance, for artificial echoes extending beyond the Guard Interval, to be degraded very smoothly, in fact similar to having a very long equalisation window. For large SFNs it has always been an issue with DVB-T/T2 that equalisation window has been quite limited in practice, so artificial echoes falling outside the guard interval (and outside the equalisation interval) have caused a much larger degradation than what would be the case if just the interference effect of the echo was considered. With distributed pilots this shortcoming could be cured and SFN behaviour would be more similar to DAB, which has this nice behaviour because it does not include channel estimation.

## **7.2. Use of dual polarisation**

In connection with DVB-T2 standardisation the idea of X-polar MIMO, i.e. using both polarisations simultaneously to increase capacity, was discussed. This idea, although technically very promising, was finally commercially rejected, mainly for the reason that such an approach did not allow any backwards-compatibility with legacy roof-top receiving antennas and would force all users (who wished to view T2-MIMO services) to replace their antenna with a new one, which was felt unrealistic. The underlying assumption was that the transmission on each polarisation would be similar to today's T2 transmissions using high-order modulation with a high required SNR, for which the polarisation discrimination of the receiving antenna would not provide enough protection.

With WiB an alternative X-polar MIMO approach potentially becomes possible. If WiB uses a much more robust transmission mode (with QPSK rate  $\frac{1}{2}$  about 17 dB more robust than DVB-T2 with 256-QAM rate  $\frac{2}{3}$ ) it could become possible to rely on the polarisation discrimination (nominally 16 dB) of the receiving antenna to achieve enough protection/separation between the two X-polar components, although this might be reduced by the practical receiving environment. One could therefore consider a WiB scenario where both polarisations are simultaneously used to transmit independent content streams, without causing harmful interference into each other. A legacy antenna could thus receive the services carried on the horizontally-transmitted component and achieve protection from the unwanted signal on vertical polarisation thanks to the polarisation discrimination. Users with a new antenna could benefit from the services from both polarisations.

It should be noted that such a solution could still be compatible with a receiver with SISO-like complexity – a new receiver would simply select the horizontal or vertical component and then process the selected component as a regular SISO signal. Choosing the polarisation would be similar to choosing the frequency today.

In a more advanced scenario, new receivers would have (at least some limited) MIMO functionality so that they could jointly MIMO-decode the two polarisations and would not have to fully rely on the polarisation discrimination.

## **7.3. TFS**

Thanks to its wideband nature WiB lends itself well to be used together with Time Frequency Slicing (TFS), which may allow close-to-ideal statmuxing also of UHD services, consistent coverage across potentially all transmitted services (or selected subset thereof) and generally increased robustness against various sorts of interference, which improves network performance and facilitates co-existence with other systems (e.g. existing DVB-T/T2 or mobile telecom systems).

TFS may be applied to WiB and could be implemented in a similar way to what has earlier been described and specified for DVB-T2 and DVB-NGH, using a single tuner or performing frequency hopping in the digital domain. The TFS-WiB signal may also employ an arbitrary subset of UHF channels in the UHF band. One interesting special case is when the TFS-WiB signal uses contiguous UHF channels, which cover the whole of or a part of the available UHF spectrum.

WiB may be used without TFS and when bandwidths become as large as e.g. 32-40 MHz the benefit of frequency diversity is somewhat reduced. However, depending on the choice of video codec (HEVC or JVET) and service quality (720p HD, 1080p HD, 2160p UHD, HDR, HFR) there may in some scenarios be a very significant statmux gain thanks to the use of a very large supermux offered by

TFS. Depending on the migration scenario, using a very large bandwidth may also help co-existence with traditional DVB-T2 networks using reuse-5 or similar.

With Scalable-Bandwidth (SB) WiB, ideally only a single wideband spectral segment could be used per transmitter site, covering all WiB transmissions from that site. With SB-WiB, using e.g. reuse-3, the total UHF bandwidth of e.g. 224 MHz (470-694 MHz) could be divided into three spectrum slots of about 74 MHz each. In this case no TFS would be needed, since this wideband signal could constitute a supermux with excellent statmuxing performance and would also have a very good frequency diversity.

#### 7.4. Scalable BW WiB

The SB-WiB (scalable BW WiB) uses bandwidths as a multiple bandwidths of the legacy DTT as following.

$$BW_{SB} = N \times BW_{Legacy} \quad (1)$$

Where N is the BW scale factor which has an integer satisfying  $N \times BW_{Legacy} \leq 224$  MHz.  $BW_{Legacy}$  is 8 MHz, the bandwidth of legacy DTT.

This scheme gives high flexibilities in selecting wide bandwidths. When  $N=1$ ,  $BW_{SB} = 8$  MHz which has the same BW with legacy DTT. When  $N=28$ ,  $BW_{SB} = 224$  MHz which has the same BW with WiB re-use 1. Due to the flexible bandwidth, the scalable bandwidth WiB may have advantages in applying wide bandwidths for DTT considering various broadcasting conditions of many countries and broadcasters.

When SB-WiB is applied, it may have following characteristics and options.

##### 1. $N=1$

When N is 1, equation (1) becomes  $BW_{SB} = BW_{Legacy}$ . The SB-WiB has the same BW with legacy DTT. Therefore there is no advantages of cost reductions in network installation and operation.

##### 2. $N=2$

When N is 2,  $BW_{SB} = 2BW_{Legacy}$ . The SB-WiB has BW 16 MHz (= 8 MHz  $\times$  2), a two times wider BW than legacy DTT. When two broadcasters use BW 16 MHz and share one transmitter, the network installation cost reduces to 1/2 but there is no transmission power saving.

##### 3. $N=4$

When N is 4,  $BW_{SB} = 32$  MHz (= 8 MHz  $\times$  4). The SB-WiB network has a configuration shown in Figure 38. When four broadcasters use BW 32 MHz and share one transmitter, the network installation costs reduce to 1/4. In this case, there is no transmission power saving.



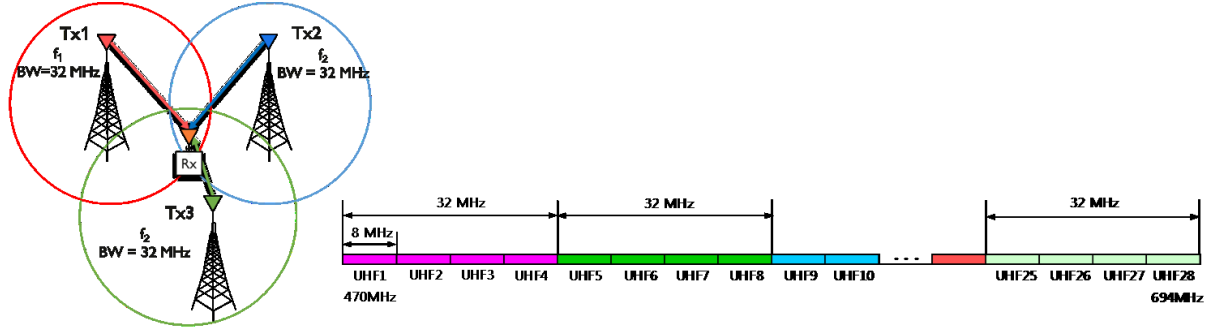


Figure 38 Frequency allocation of SB-WiB BW 32MHz

When two broadcasters use BW 32 MHz, 16QAM can be used instead of 256QAM for data rate 40 Mbps for each broadcaster. In this case, the reduction of transmission powers can be obtained as well as the network installation cost reduction in half. In this case each broadcaster may use half of effective bandwidth 30.44 of SB-WiB 32MHz. In DVB-T2 Implementation Guideline, the QEF(quasi error free) CNRs for 256QAM CR=2/3 and 16QAM CR=2/3 are 20.1dB and 10.8 dB in Rayleigh channel respectively and the QEF CNR difference is 9.3 dB. The transmission power of SB-WiB can be computed as following.

$$P_{saving} = \frac{BW_{SB}}{BW_{legacy}} \times \frac{1}{10^{\frac{CNR_{diff}}{10}}}$$

$$= \frac{\left(\frac{30.44}{2}\right)}{7.61} \times \frac{1}{10^{\left(\frac{9.3}{10}\right)}} \approx 0.23$$

Where  $BW_{SB}$  is the effective bandwidth of SB-WiB 30.44 MHz and  $BW_{legacy}$  is the legacy BW 7.61 MHz,  $CNR_{diff}$  is the QEF CNR difference between 256QAM CR=2/3 and 16QAM CR=2/3.

Therefore when 16QAM is used in half band of SB-WiB 32MHz, for about 40Mbps data rate it requires only 23% transmission power of 256QAM in legacy bandwidth 8 MHz, i.e. 77% of transmission power can be saved.

	Modulation	Spectral Efficiency [bit/Hz]	Effective Bandwidth [MHz]	Data Rate [Mbps]	Tx Power
Legacy DTT	256QAM CR=2/3	5.31	7.61	40.4	<b>1</b>
SB-WiB	16QAM CR=2/3	2.66	15.22	40.5	<b>0.23</b>

※ Spectral efficiencies are quoted from DVB-T2 Implementation Guideline(ETSI TS 102 831 v1.2.1 2012-08)

#### 7.4.1. Gains in spectral efficiency

The comparison of GB (guard band) size is shown in Figure 39 for SB-WiB and the legacy DTT. The legacy DTT has GBs for every 8 MHz. But SB-WiB has a guard band every 32 MHz (when N=4). For SB-WiB, the spectrum for GBs is decreased to 1/N. For DVB-T2 of BW 8MHz, the GB size is about 0.39 MHz. Therefore for SB-WiB of N=4, the spectrum gain  $S_{GB}=0.39 \times (4-1)=1.17$  MHz is obtained.

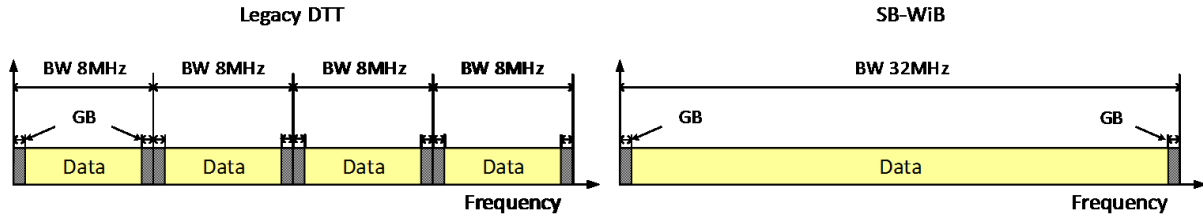


Figure 39. Guard bands in an OFDM symbol of legacy DTT and SB-WiB BW 32MHz

#### 7.4.2. Flexibility for the soft transition of DTT

The SB-WiB has various BW options according to  $N$ , the BW scale factor. In the transition period of DTT system, the legacy DTT and SB-WiB do not interfere with each other, by allocating the SB-WiB in a different frequency band from the legacy DTT as shown in Figure 40.

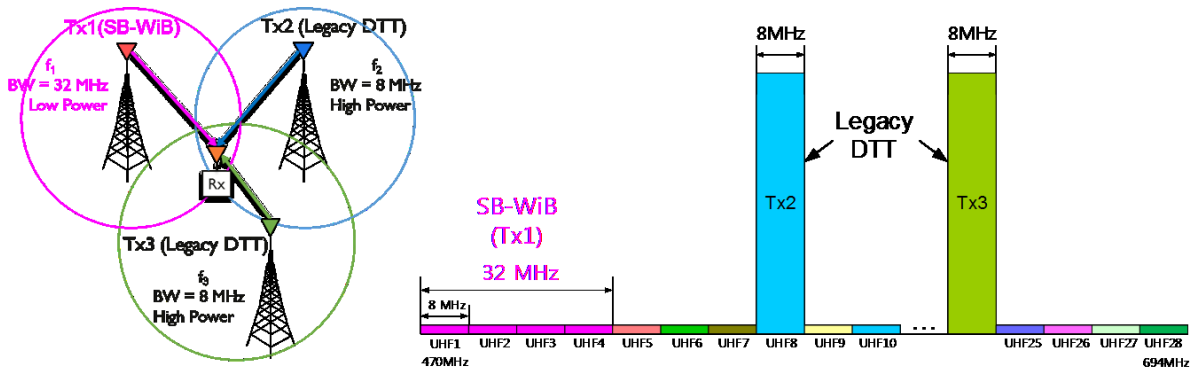


Figure 40. Frequency allocation for SB-WiB BW 32 MHz in transition period

#### 7.4.3. Application of SB-WiB

##### 7.4.3.1 Application for DVB-T2 compatible

The application of SB-WiB for DVB-T2 compatible is shown in Figure 41. In this case, the guard bands exist in SB-WiB spectrum. Because  $N$  broadcasters use only one transmitter, the network installation cost and maintenance cost can be reduced.

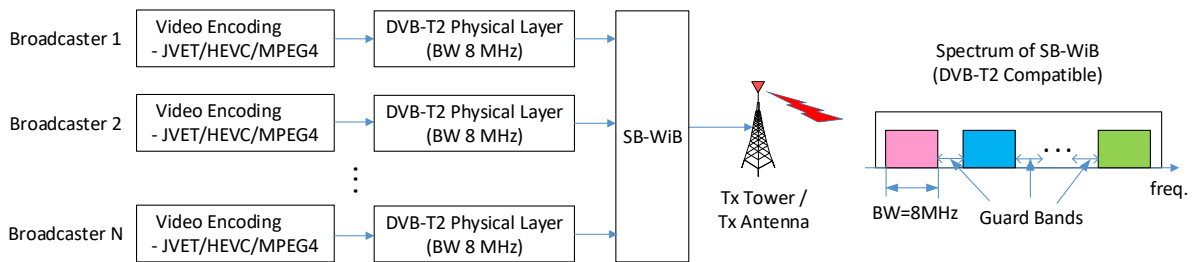


Figure 41. Application of SB-WiB for DVB-T2 compatible

##### 7.4.3.2 Application for a new DVB DTT system

The application of SB-WiB for a new DVB DTT system is shown in Figure 42. In this case, the guard bands between the legacy 8 MHz bandwidths are removed, which results in some spectrum gains. Network installation costs and transmission power can be reduced as explained in  $N=4$ . In a wide

bandwidth, a new interleaving scheme may be applied and result in some frequency diversity gains too.

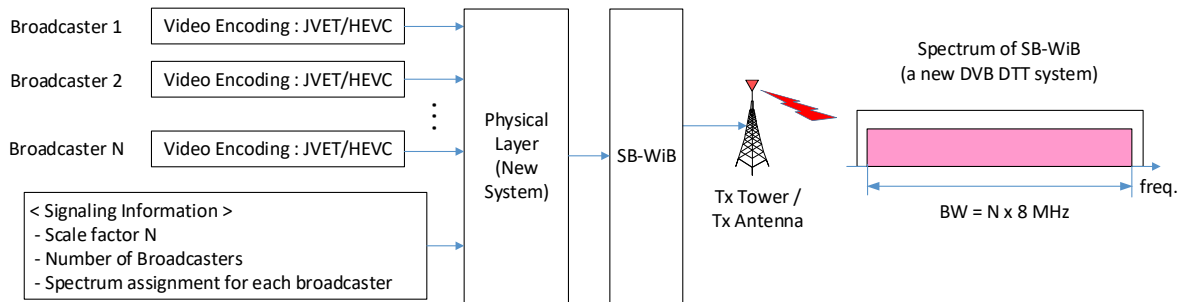


Figure 42. Application of SB-WiB for a new DVB DTT system

### 7.5. Backwards compatible re-use-1

This section analyses the potential of backward compatible re-use-1 solutions for fixed DTT services, i.e. using DVB-T2. Thus wideband carrier aggregation and interference cancellation cannot be used, Gaussian demapping is assumed, as in conventional DVB-T2 receivers, so interference is treated as noise.

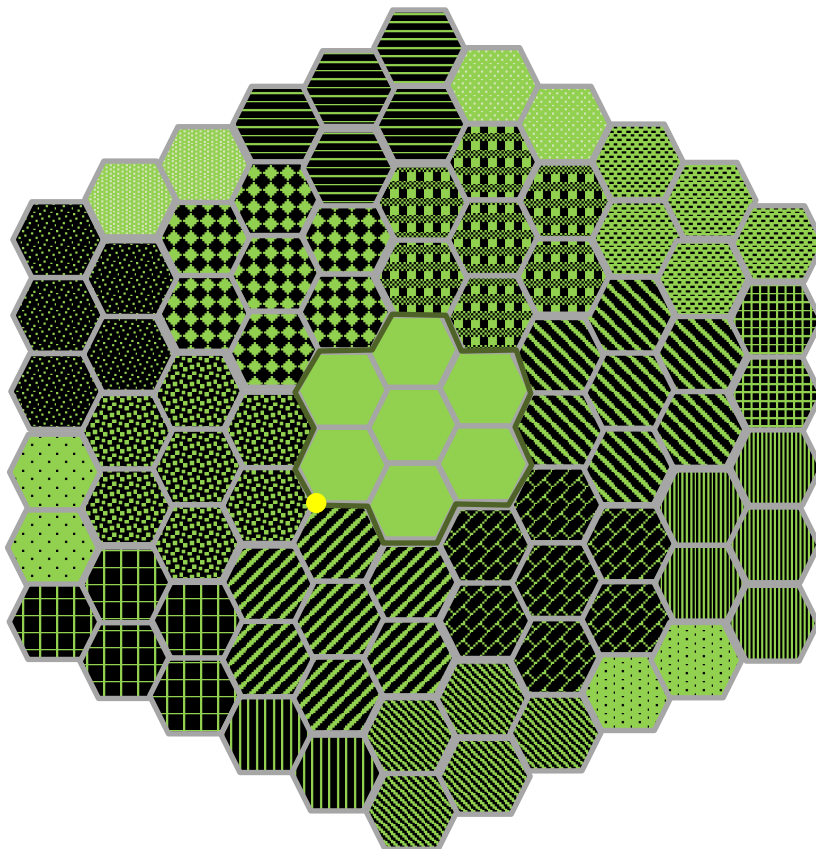


Figure 43. Transmitter network lattice. Re-use-1, 7 cell SFN cluster. Yellow point represents worst receiving point

The simulated network structure is the 91-site hexagonal transmitter lattice of Figure 43. Additional tests have also been carried out with an additional outer ring of transmitters, resulting in a network

of 127 transmitters. The transmitters operate in Frequency re-use-1 in 7 cell cluster SFNs. The yellow point represents worst receiving point.

Monte Carlo simulations were used to calculate the SINR for each receiving point of the testing area, based on the Best Transmitter per Location technique (see section 4.3.3).

The target percentages in the small areas have been set at 95% for "good" and 70% for "acceptable" reception.

A Guard Interval of 448 $\mu$ s was assumed.

The same parameters were used as for the hexagonal simulations of section 5.1, except that transmit antennas with the vertical radiation pattern shown in Figure 44 have also been simulated. In the case of vertical directional antenna, the radiation pattern is tilted downwards to reduce interference at the horizon, to have a 3 dB attenuation at the edge of the coverage area (as a good compromise between high useful field-strength at the service area edge and interference reduction from surrounding transmitters).

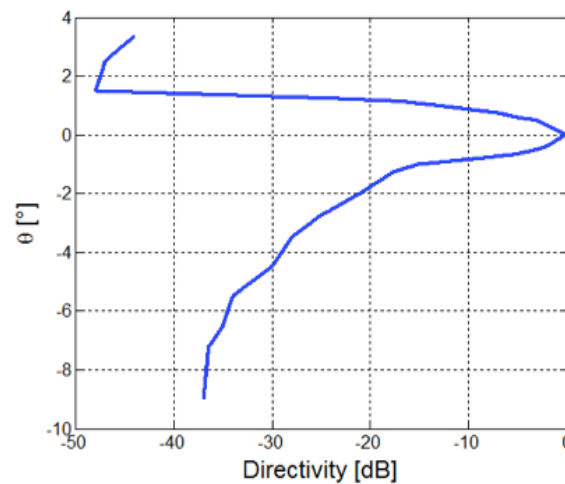


Figure 44. Transmitter vertical antenna pattern for 0° tilt

The study concentrated on fixed roof-top antenna reception, at 10 m agl, assuming an antenna pattern defined in [17]. This antenna has a gain of 9.15 dB in the range  $\pm 20^\circ$ , falling linearly from 9.15 dB at  $\pm 20^\circ$  to -6.85 dB at  $\pm 60^\circ$ , and a front to back ratio of 16 dB. Furthermore, to improve capacity at the border of the SFN, receiving antennas with improved front/back discrimination have been considered, with a front/back ratio FTB=26 dB (available in commercial UHF antennas, see for example Fracarro LP45NF [23]).

In Figure 45 the SNR and spectral efficiency versus the outage probability in the worst point of the SFN cluster are plotted for conventional receiving antenna (Figure 45(a)) and for improved FTB receiving antenna (Figure 45(b)). The improved antenna allows to achieve 2.3 bit/s/Hz in 95% of the locations in the worst area. In about 60% of the locations in the worst area the target capacity is also achieved with a conventional FTB antenna. The improved FTB antenna is required in about 35% of the locations in the worst area to achieve the target capacity. Figure 46 shows the effective spectral efficiency [bit/sec/Hz] variation from the worst point, along the (white) line in the hexagon at 95% Location Probability. From the figure, the resulting percentage of receiving antennas in the 7

cell cluster to require improved FTB to achieve the target 2.3 bit/s/Hz in 95% of the locations is less than 4%.

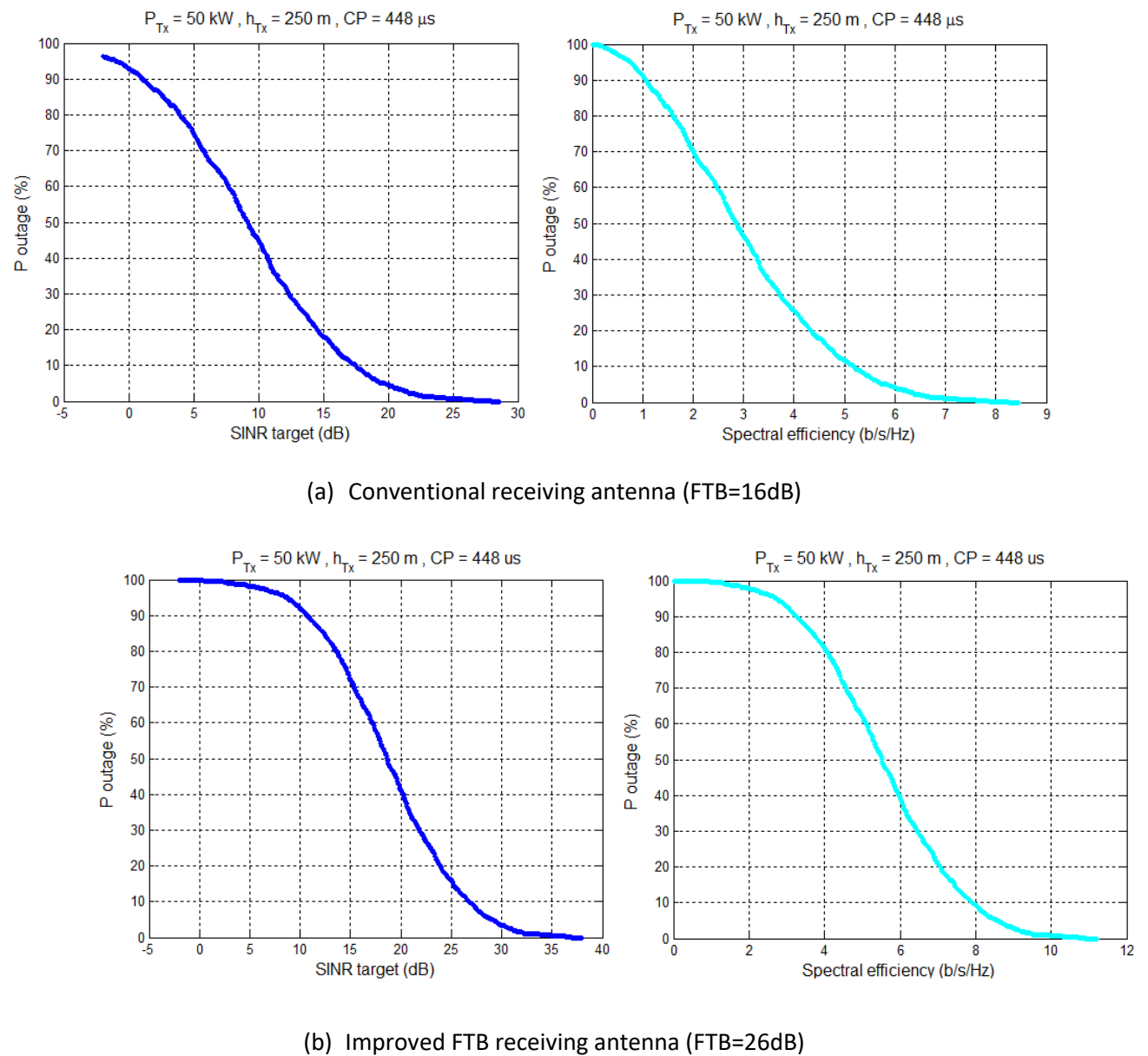


Figure 45. SNR and spectral efficiency versus the outage probability in the worst point of the SFN cluster

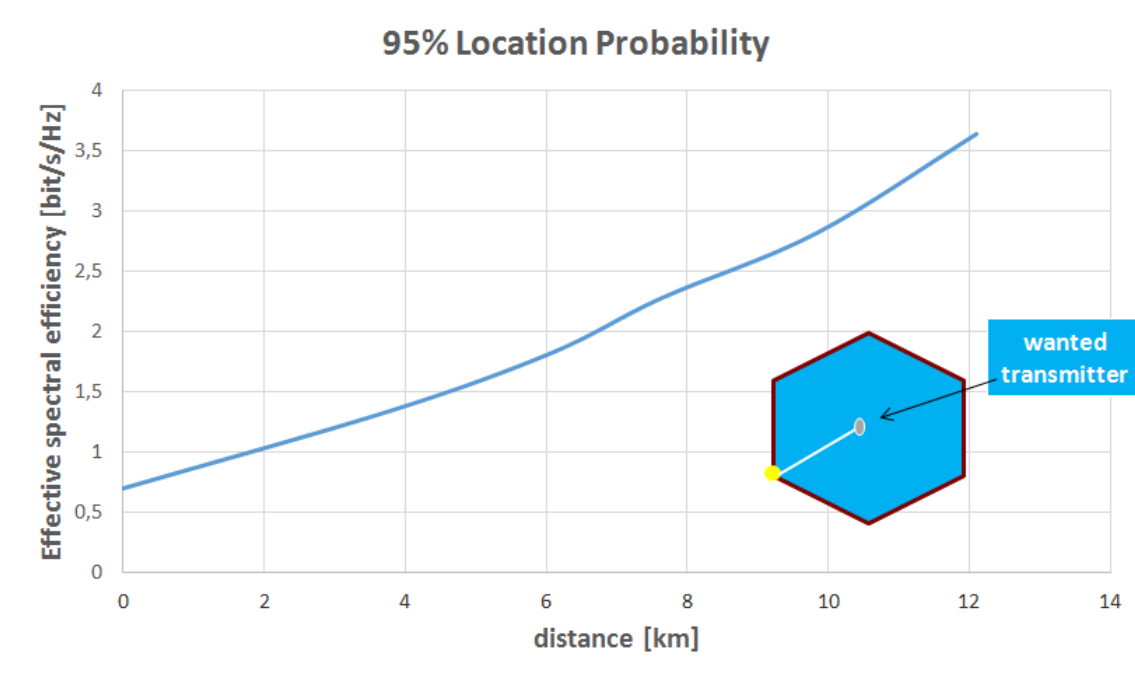


Figure 46. Effective spectral efficiency [bit/sec/Hz] variation from the worst point, along the (white) line in the hexagon at 95% Location Probability

In figure 47 the effect of the transmitter EIRP is plotted: to have a fair comparison of power consumption for configuration using different reuse factors, the value in abscissa the Normalised Power, that is TX EIRP/Reuse factor. So it means that for Reuse-1 the value in abscissa is the effective Tx EIRP, while for Reuse-N each transmitter uses one frequency out of N with a power N times the value in abscissa.

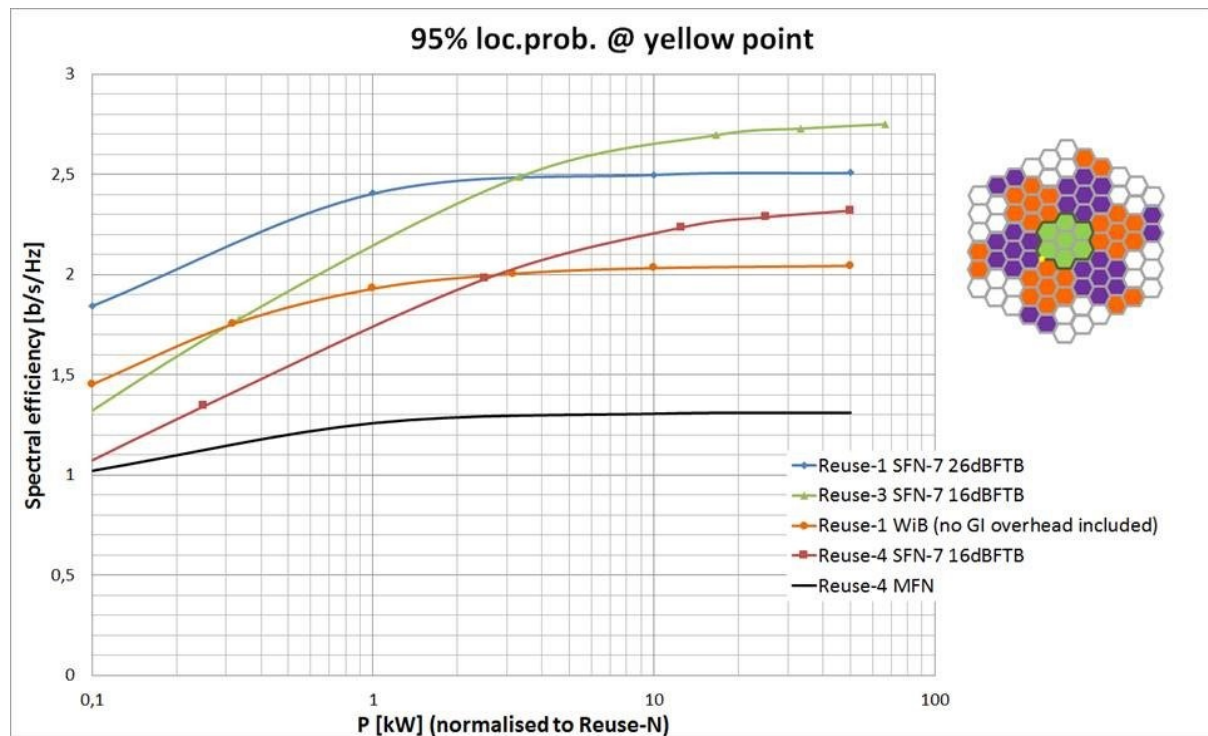


Figure 47. Effect of the Transmitter EIRP on the achievable spectral efficiency

With EIRP measured @90% of maximum capacity, the results at 95% coverage of worst pixel could be summarised as follows for the different configurations:

- Reuse-3 achieves 2,5 bit/s/Hz at 3 kW normalised EIRP, i.e. with each transmitter of the network having an EIRP of 9kW.
- Reuse-1 achieves 2,2 bit/s/Hz at 0,5 kW transmitter EIRP, using the 26dB FTB antenna
- Reuse-4 achieves 2,1 bit/s/Hz at 5 kW normalised EIRP, i.e. with each transmitter of the network having an EIRP of 20kW.
- 
- WiB (Shannon diamond) achieves 1.95 bit/s/Hz 1 kW

The case of Vertical directive transmitting antennas is given in Figure 48, where it is evident a slight increase of the achievable spectral efficiencies in all configurations, at the expenses of a higher EIRP.

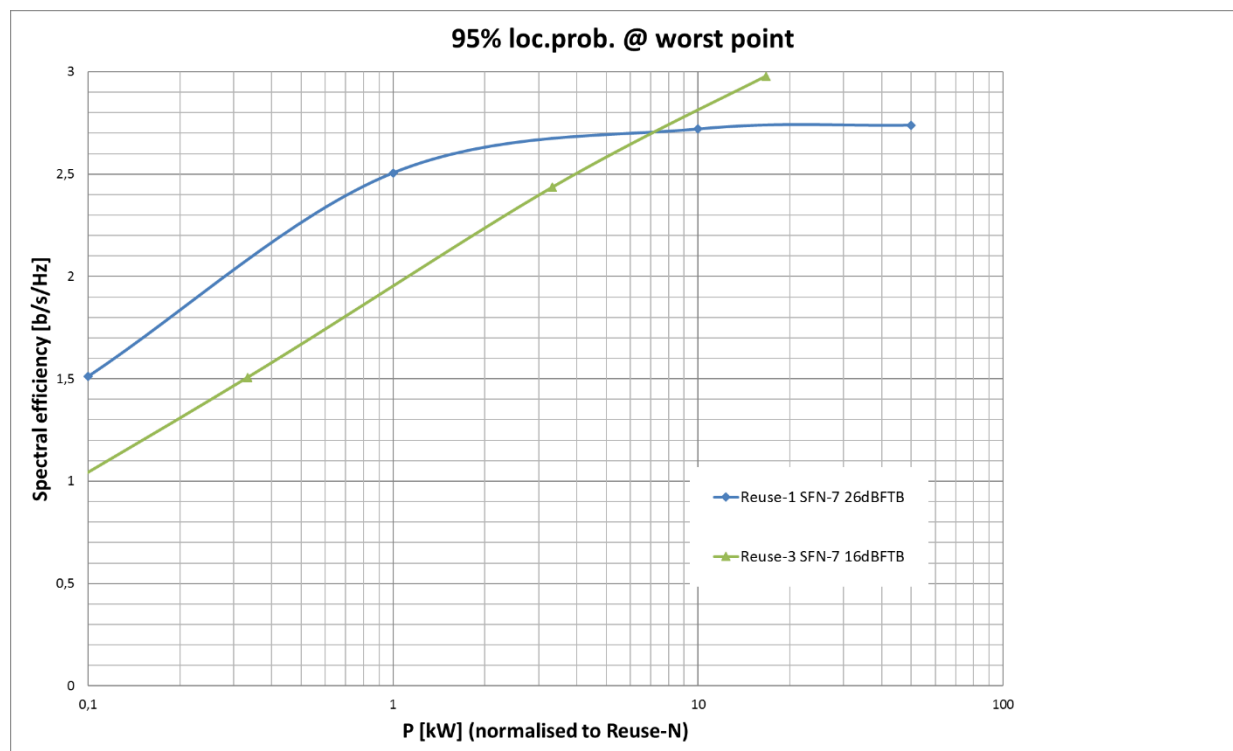


Figure 48 Effect of the Transmitter EIRP on the achievable spectral efficiency (Directive Vertical pattern of the Tx antenna)

## 7.6. Antenna-based cancellation

As an alternative to the Joint Iterative Demapping & Decoding (JIDD) interference cancellation approach, which works with SISO transmission, a more powerful antenna-based interference cancellation technique may be used. In some scenarios such a solution may allow a far greater spectral efficiency than the simpler JIDD approach. This approach may also be combined with X-polar MIMO, if desired.

The main idea is to use a (typically) roof-top antenna, similar to current roof-top antennas, but with two small additional “helper antennas”, which could themselves be very simple, e.g. dipoles. Ideally,

the helper antennas should have some limited gain and front/back ratio (e.g. 3 dB) to facilitate the cancellation process.

In the worst point of a hexagonal network, with signals being received from three neighbouring transmitters or SFN areas (each of them being considered as a single “SFN signal”), there would essentially be three main received signals, with one of them being the wanted signal and the other two being interferers. In addition, there would be “far-away” interference from transmitters beyond these three transmitters, or SFN clusters. Similar to a MIMO situation three signals being received by three antennas may, depending on the total transmission channel, potentially allow all three signals to be received. By using e.g. “zero forcing” the  $3 \times 3$  matrix, characterising the overall transmission/reception, is simply inverted, which yields the three signals. But there are also more advanced schemes, which may handle more complex reception cases. It is however unclear whether such functionality is needed for the type of reception cases described.

In our case we are normally only interested in one of the signals, so the other two do not need to be decoded – the signal vectors of these signals just need to be used for the cancellation process and for this the receiver needs the appropriate channel estimation of all three signals, which can be achieved using orthogonal pilots, see above.

The above-described scheme is typically able to completely eliminate the two interfering signals, but may in the general case have some unpredictable effect on the wanted power  $C$ . However, with antenna types, as described, any negative impact on  $C$  should normally be minimal.

After cancellation the resulting available  $C/(N+I)$  in the reception point is then dependent on the power  $C$  of the wanted signal, the noise power  $N$  and the “far-away” interference power  $I$ , which tends to be low. Assuming interference is in practice the main limiting factor this means that the achievable spectral efficiency is a direct function of the received “far-away” interference. For the achievable spectral efficiency it should therefore be very desirable to reduce the level of this “far-away” interference.

There are two very powerful ways by which this interference may be reduced, and the  $C/I$  increased and the spectral efficiency increased:

1. Using SFN clusters
2. Using vertical antenna diagrams with some down-tilt

By using *SFN clusters* the distance to the nearest “far-away” interferer is drastically increased with corresponding reduction in received interference. This is very beneficial and allows for a very large increase in spectral efficiency. In principle, “the larger, the better” should apply in this case (within some limits), but the size of the SFN area should be balanced against the requirements for granularity of regional or even local services.

Transmitters may use a certain degree of *vertical down-tilt* of the transmitted signal. This means that the maximum of the vertical antenna diagram is directed to a point somewhat closer to the transmitter than the cell edge, which is otherwise preferred, if one wants to maximise the received SNR at the cell edge. The downside of this is that the SNR of the wanted signal at the cell edge is somewhat reduced. The upside is, however, that the radiated power in the direction of the horizon can be attenuated far more. In one example diagram the wanted power is decreased about 3 dB at



the cell edge but the received interference from far-away transmitters (horizon) at the cell edge is decreased by 13 dB, i.e. there is in this case a potential net gain in  $C/I$  (for such interfering transmitters) of about 10 dB at the cell edge, which is huge!

These two techniques (1) and (2) play well together, since large SFN clusters (1) not only make the far-away interference come from a larger distance (i.e. weaker) but also allows the vertical antenna diagram to have a more fully-developed attenuation at these distances.

The complexity of this scheme is limited from the physical receiving antenna perspective, in fact similar to today's active antennas. What would need to be added is the two small helper antennas as well as simple signal processing for frequency separation of two of the signals to allow for single-cable download. The receiver could have a single antenna input, as today. The complexity of the receiver itself is larger than T2 today, since up to three signals need to be combined. However, the resulting FEC decoding (being one of the most complex parts of the receiver) does not need to be duplicated, but can be used more or less as today in T2.

### 7.6.1. Results

The achievable spectral efficiency for purely interference-limited coverage has been evaluated in some critical points in a 7-TX SFN cluster network, see Figure 49.

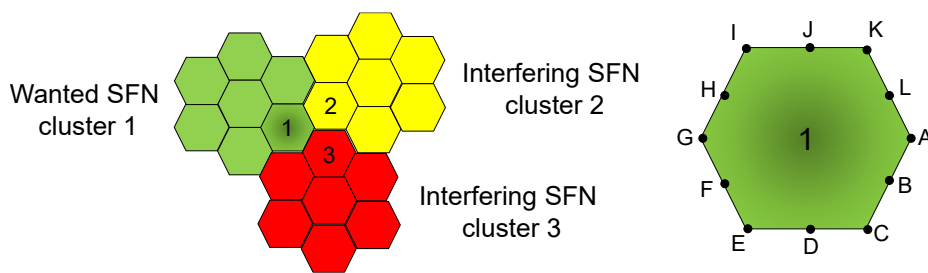


Figure 49. Critical points for evaluation in a 7-cell SFN cluster with antenna cancellation

With the assumption that in a particular reception point either 0, 1 or 2 adjacent SFN clusters could be fully cancelled (i.e. "SFNx=0") according to the Table 1, the performance in Table 2 was obtained by computer simulations:

A: TX1 (SFN2=0, SFN3=0)  
 B: TX1 (SFN2=0, SFN3=0)  
 C: TX1 (SFN2=0, SFN3=0)  
 D: TX1 (SFN2=0, SFN3=0)  
 E: TX1 (SFN3=0), TX5 (SFN2=0, SFN3=0)  
 F: TX1 (SFN3=0), TX5 (SFN2=0, SFN3=0)  
 G: TX1 (No IC), TX5/TX6 (SFN2=0, SFN3=0)  
 H: TX1 (SFN2=0), TX6 (SFN2=0, SFN3=0)  
 I: TX1 (SFN2=0), TX5/TX6 (SFN2=0, SFN3=0)  
 J: TX1 (SFN2=0), TX7 (SFN2=0, SFN3=0)  
 K: TX1/TX7 (SF2=0, SFN3=0)  
 L: TX1 (SF2=0, SFN3=0)

Table 1 – Assumptions on cancellation ability at various reception points and for different antenna directions

	0 dB		3 dB		10 dB
A	4,8		5,7		7,4
B	6,2		7,3		9,5
C	4,8		5,5		7,2
D	5,4		6,1		8,0
E	3,9		4,3		5,7
F	4,7		5,5		7,4
G	4,0		5,2		6,5
H	6,2		7,2		8,8
I	5,2		6,0		7,5
J	5,2		6,0		7,5
K	5,2		6,0		7,5
L	5,0		6,2		7,5

Table 2 – Achievable spectral efficiency (interference-limited coverage) at different reception points and with different assumptions on TX antenna vertical downtilt attenuation

### 7.6.2. Estimated overhead for a network with large SFN clusters (7-TX SFN)

#### GI overhead factor - OH1

Required GI for 60 km ISD = 400 us (2 x ISD)

With 32K FFT:  $T_u = 3584$

$$OH1 = (3584 - 400) / 3584 = 0.888$$

#### Pilot overhead factor - OH2

OH2 = 0.95 (see above)

#### Preamble overhead - OH3

Assuming a 400 ms frame with 4 ms total symbol time ( $T_u + G_I$ ) → 100 symbols per frame

Assuming preamble uses 3 full 32K symbols →  $OH_3 = (100-3)/100 = 0.97$

Total overhead factor =  $OH_1 \times OH_2 \times OH_3 = 0.888 \times 0.95 \times 0.97 = \mathbf{0.82}$

Realistic spectral efficiency with 5.333... bps/Hz Shannon →  $5.333 \times 0.82 = \mathbf{4.37 \text{ bps/Hz}}$

(using same MODCOD/TX power as today per 8 MHz channel, but with reuse-1)

### **7.7. Required alignment and synchronisation to allow for Interference Cancellation**

For interference cancellation to work (with reasonable complexity) the respective signals on either side of a content border need to be aligned and synchronised, i.e. using the same physical-layer configuration and scheduling – only the content (and reference information) can be different. To support variable-bit-rate (VBR) services in dedicated PLPs this means – in contrast to DVB-T2 and DVB-NGH – that the traditional PLP configuration needs to be fixed and using a constant bit rate, whereas the service-to-PLP mapping may be dynamic, following the VBR nature of the service. This means that the PLPs that are actually used to carry a service varies over time, which is signalled to the receiver. For the actually-used PLPs interference cancellation may then be applied, and with the aligned and synchronised PLPs the cancellation can be performed with minimum complexity. For interference cancellation this type of alignment and synchronisation needs to be performed irrespective of whether the WiB signal uses TFS or not. For WiB scenarios where interference cancellation is not used there is no need to perform such alignment and synchronisation.

- Discuss receiver complexity

### **7.8. Transposers for WiB**

At first glance it may look like transposers (i.e. frequency-changing repeaters) cannot be used with WiB since WiB uses all spectrum already from the normal transmitters, so there seems to be no spectrum left for transposers when WiB is used in all UHF spectrum.

However, there appears to be a possible technical solution for transposers also together with WiB, provided the total spectrum required by the retransmitted services is no more than half the total WiB spectrum. In this context it may be noted that in the current DTT networks in UK and Sweden this condition is fulfilled (UK: only 3/6 of muxes, Sweden: Only 1/6 of muxes).

The basic idea is that services are arranged in the transmitted signal in such a way that a simple frequency shift will move services to be retransmitted (“A services”) into the frequency locations of services not to be retransmitted (“B services”). A simple example of this is when e.g. retransmitted services use odd UHF channels and non-retransmitted services use even UHF channels. A frequency shift of one UHF channel (typically 8 Hz) would then shift service according to the condition above.

In connection with the frequency shift the input signals on channels not to be retransmitted would be filtered out by the transposer, allowing the just frequency shifted to replace it at this frequency position.

The only remaining interference would then be between the main transmitter B services (transmitted e.g. on even UHF channels, following the example above) and retransmitted A services using the same UHF channels. For a receiver this would not be different from a general interference

situation in the network and “standard” WiB interference cancellation functionality may be used. However, for this to work the retransmitted A services need to have orthogonal pilot patterns to the B services to allow for independent channel estimation. For an illustration of the scheme, see Figure 50.

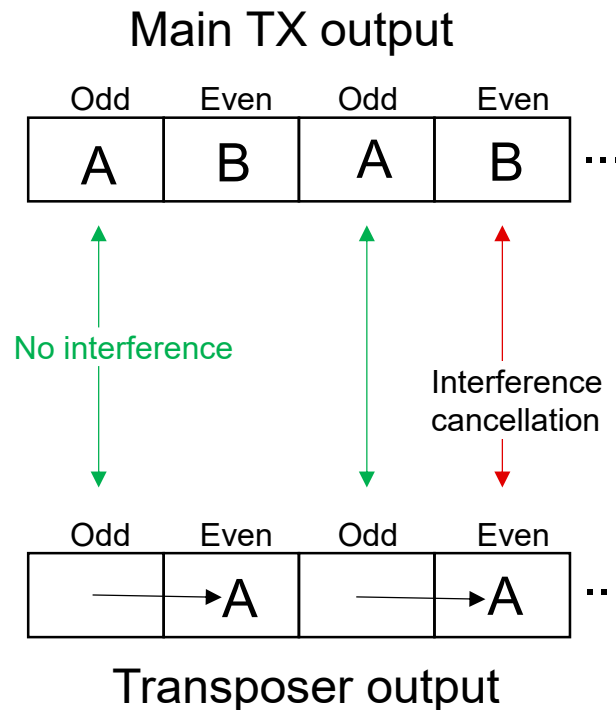


Figure 50 Principle illustration of transposer operation together with WiB

### 7.9. LDM used to provide differential levels of service

As was discussed in section 5.3.1, the existing UK network provides different coverage for different multiplexes (and therefore services). Only the three “Public Service Broadcasting” (PSB) multiplexes reach the 98.4% population, whilst the three “commercial” multiplexes serve only around 90%. The WiB networks studied above would deliver all the services to the 98.4% of the population. This makes comparison difficult, since there is no single figure that represents the number of multiplexes.

This suggests a possible alternative scenario. The WiB network could transmit Layer Division Multiplexed (LDM) signals, with the PSB services in the upper (more robust) layer and the commercial services in the lower layer. Using all 28 UHF channels, the upper layer could provide 120Mbit/s, the equivalent of three UK-mode DVB-T2 multiplexes, whilst needing only 0.54bit/s/Hz. This is well below the capacity available for QPSK at 98.4% coverage in the WiB results above, implying that such a signal could readily tolerate the presence of a lower layer. The results for 16-QAM at 90% coverage suggest that a total bit-rate (for both layers) in excess of 2bit/s/Hz could be available; in other words, the commercial services may be able to achieve a similar coverage to the existing commercial multiplexes whilst delivering a total bit-rate, for the households that are able to receive the lower layer, that exceeds the current bit-rate by a factor of two or more.

The bit-rates allocated to the PSB and commercial services could be traded off, but increasing the PSB bit-rate would reduce the total bit-rate available. However, further work would be needed to establish the exact bit-rates available and the trade-offs that could be made.

## **8. Approaches to transition**

TM-WiB0078, a real world study, briefly investigated the possibility to introduce WiB in the UK, post 700MHz clearance. The study focussed on the potential of launching a very low power WiB service, covering around 50% of the population, by interleaving it amongst the existing high power DTT services; a context very similar to the way that low power DTT was launched alongside analogue services in the 1990s. No mention was made of the capacity that the WiB service may achieve.

After considering a number of scenarios, all based on the introduction of low power WiB services at 42 main stations (all horizontally polarised in order to protect vertically polarised relays), and utilising between 18 and 21 interleaved frequency channels, the study concluded the following:

Introducing WiB interleaved with post 700 MHz clearance DTT services, does not appear to be feasible. Based on the UK example, the predicted impact to DTT, even with WiB operating 26dB below the main multiplexes, would be unacceptable. A similar study in France (limited to the area round Paris) came to the same conclusion.

In the case of UK, harmful interference could, however, be mitigated by coordinating WiB's introduction with a DVB-T2 migration. It was found that adopting modulation schemes more robust than those on air today could enable the existing coverage and capacity of DTT to be maintained while allowing WiB to be introduced.

Although this approach would preserve the DTT platform's existing capacity, it would however, lead to a reduction of 51 Mb/s relative to the potential capacity of the DTT multiplexes without WiB. The benefits of WiB would therefore have to be balanced against this lost potential capacity. In order to be considered viable, the new WiB service would need to provide significantly more capacity than would be lost, or at least promise more in the future.

It therefore appears that in the UK context a scenario exists which would allow WiB to be introduced by interleaving it with the existing multiplexes within the DTT spectrum. However, doing so would require a coordinated effort to transition the existing services to DVB-T2 using more robust modes than would otherwise be needed. In order to determine whether such an approach was worthwhile the associated loss of potential capacity would need to be balanced against the potential benefit of WiB. Further work is also required in order to determine whether the scenario investigated would be compatible with transmissions from other countries.

Regarding the impact of existing DTT networks on WiB coverage and capacity, using the interleaved spectrum during transition, document TM-WiB00104 simulates a regular DTT MFN network with two reuse factors, 4 and 7. It calculates the expected C/I at the WiB receiver in the worst coverage location of the network. The results show that:

In a scenario of MFN reuse 4 network, the WiB receiver will need to cope with high levels of interference from co-channel DTT transmitters, from geographically adjacent as well as distant co-channel transmitters. Taking into account:

- a) 17 dB power back-off of the WiB transmitter using interleaved spectrum;
- b) 16 dB front-to-back antenna discrimination of the geographically adjacent DTT co-channel interferer;
- c) The contribution of distant co-channel DTT interferers,

the expected C/I at the worst reception location (edge of coverage) would be negative (around -4 dB predicted with median levels) in two thirds of the available interleaved channels – i.e. the DTT interference would be 4dB stronger than the wanted WiB signal. The results are more favourable for WiB in a reuse 7 DTT MFN network (around -3 dB C/I, predicted with median levels) in one third of the available interleaved channels.

This would constrain significantly the expected WiB capacity in this transition scenario, unless interference reduction solutions are introduced in the WiB receiver with regard to DTT interferers. These solutions could be:

1. To improve the front-to-back attenuation of the receiving antenna for WiB. However, this applies only to roof top reception of WiB channels and refers rather to an ideal situation since antennas will suffer from reflections (decreasing the effect of enhanced FTB ratio). Furthermore, even in the ideal case of no reflection, the good FTB performance of the antenna is not available on the whole UHF band as shown by real measurements (varying FTB ratio depending on the channel, and presence of some secondary lobes on some channels).
2. To implement an interference cancellation technique for DTT interference in the WiB receiver able to cope with at least two DTT interferers. This would improve the WiB coverage and capacity for both fixed and portable reception. However, no studies have been done on the feasibility or the effectiveness of this solution. Note that the interfering DTT signal will not necessarily be synchronised with the WiB signal nor have the appropriate pilot signals (in particular in the case of cross-border interference without pre-coordination between neighbouring countries) which will make such cancellation more complicated than the cases discussed elsewhere in this report for cancelling WiB signals,

### **8.1. T2-WiB - Backwards-compatible extensions to DVB-T2**

#### Orthogonal and distributed pilots

Preliminary studies suggest that it is probably possible to extend the existing DVB-T2 standard in a backwards-compatible way to support interference cancellation and other functionalities that are associated technologies to WiB.

As mentioned elsewhere in this report, to support interference cancellation there needs to be orthogonal pilot patterns between different transmitted signals, fundamentally between the pilots from different adjacent transmitters or SFN clusters (regions). To keep the overhead low and to allow for some other desirable functionality it may also be desirable to allow for a dedicated pilot pattern from each transmitter in an SFN cluster. Neither of the above is however currently supported by DVB-T2.

DVB-T2 includes however reserved bits for the signalling field PLP\_PAYLOAD\_TYPE. The idea is to specify a new PLP\_PAYLOAD\_TYPE for Data PLP Type 2 and to carry reference signalling on that PLP

instead of normal data. The reference signalling would, as existing data PLPs, come in multiples of one FEC block worth of OFDM cells, i.e.  $n \times 16200$  cells or  $n \times 64800$  cells, but would include complex pilot values, for active pilot positions, or the value zero for null cells.

On the modulator side such PLPs would be time interleaved and sub-sliced together with other Type 2 PLPs. Before frequency interleaving these pilot positions could then have a regular pattern along the frequency axis in an OFDM symbol, but would after frequency interleaving appear at quasi-random positions.

A legacy T2 receiver would simply discard these PLPs, since the `PLP_PAYLOAD_TYPE` is unknown.

A new receiver would need to perform the channel estimation based on the quasi-random distribution of pilots, but in theory this should only have a minor importance. The pilot orthogonality would be kept across the frequency interleaving.

#### New preamble in the FEF part

In some reception conditions the interference situation may be too demanding for a legacy T2 receiver, both from the point of view of “steady-state” reception, but also from the point of view of Synchronisation, Signalling and Sounding (SSS). To allow robust SSS performance also in cases of severe interference it may be required to introduce a new, more robust, preamble.

The new preamble may be introduced in a T2 FEF part and could e.g. include the required support for estimation of relative delays for the distributed pilot concept. A legacy T2 receiver is expected to simply discard the FEF part (since it is unknown), whereas a new receiver could synchronise on this and use it in the intended way.

Together the new distributed pilots and the new SSS signalling should allow a new receiver to perform interference cancellation in severe interference conditions. The provided extensions would allow both JIDD-based and antenna-based interference cancellation.

#### X-polar MIMO

The dual-polarisation approach described above may be introduced in a backwards-compatible way, with a horizontally-polarised T2-WiB signal being received by legacy horizontal-polarised antennas and an additional vertically-polarised T2-WiB signal received by a new antenna and receiver.

Both components could use the distributed pilot approach, which would allow the pilots of the two components to be orthogonal. In this way the new receiver could use the two polarisations jointly and allow reception also in cases where the polarisation discrimination does not offer enough protection for independent reception of either signal.

#### LDM

A lower LDM layer may easily be added below a legacy T2 (or T2-WiB) signal. The lower-layer signal may be of the same 8 MHz T2-WiB type or even be a full-blown WiB signal (i.e. wideband). In both cases the existence of the lower layer can be signalled by reserved L1 signalling bits.

In all cases above the “core” component of a transmitted T2-WiB signal could be received by a legacy T2 receiver when reception conditions so allows.

## **8.2. Impact of WiB implementation on PMSE**

With WiB using the entire 470-694 MHz UHF spectrum, the situation whereby DTT is the primary allocation and the white space resulting from interleaved planning is used on a secondary basis for PMSE applications ceases to exist, and it may appear as if no PMSE applications would be possible in the same band.

From the point of view of PMSE interfering into WiB, this does not appear to be such an issue given the characteristics of WiB broadcasts, even when the possible PMSE interference is near the point of reception, however the bodies responsible for spectrum management at international and national level would need to thoroughly review all their allocation, authorisation and licensing procedures and processes. Currently, authorisation for PMSE applications is not normally available for co-channel allocations.

If the authorisation issues can be overcome, then co-channel interference from WiB into PMSE will need to be considered and there are a number of aspects which would need to be taken into account.

Firstly, WiB is likely to be transmitted with a far lower (e.g. 17 dB) spectral density than current DTT, so should offer an extra interference margin.

Secondly, in locations far away from the broadcast transmitter, the WiB field strength levels – measured in the typical PMSE bandwidth of 200 kHz (i.e. much lower than in 224 MHz or 8 MHz) - are low and in a significant area around a PMSE transmitter the resulting C/I is likely to be sufficient for PMSE operation. Increasingly, however, the audio PMSE equipment manufacturers are producing multi-channel systems that utilise a larger bandwidth; for these systems the resulting C/I may be insufficient.

Finally, the situation where PMSE usage is performed exclusively indoors, e.g. in some TV studios with a degree of protection via the wall penetration loss, may be improved with WiB adoption. However, there are a significant quantity of entertainment, production and sporting events that are hosted outdoors and many of these require the highest number of channels.

These factors together make it likely that PMSE, from a technical point of view, could co-exist with WiB in the UHF band in more use cases than it can with current DTT networks, subject to the spectrum management issues being overcome. However, in the event of a complete loss of UHF spectrum to PMSE there will be insufficient spectrum to sustain current PMSE usage levels, which would severely impact content production. Taking the UK as an example, there is approximately 30 MHz available in CEPT designated bands other than UHF for wireless audio PMSE, and potentially another 50 to 60 MHz in metropolitan areas from the so called “air band” (960 – 1164 MHz – which is not currently harmonised in Europe and for which there are no devices currently on the market). This must be seen against current UHF usage of 176 MHz or more at a single location.



## **9. Conclusions**

The previous sections have presented and attempted to interpret the results from the studies undertaken within TM-WiB to assess the benefits of WiB. These have shown a wide range of results, from a significant capacity loss in some situations to a potentially worthwhile gain in others. It should be remembered that detailed planning studies have only been undertaken in the UK case, and that these results might not be more generally applicable, but also that in the time available it has not been possible to undertake practical system simulations, so the extent of any potential gains have not been verified, and they may in practice prove to be considerably reduced.

Whilst at face value, if the largest potential gain were fully realised, it might be attractive in a like-for-like system change (as was the case when moving from DVB-T to DVB-T2), WiB involves much more than a like-for-like change. WiB would require a significant change of approach to planning which could be very difficult to coordinate across Europe, and the gains would only be realised if it was widely or universally adopted, since transmissions between all neighbouring countries need to be synchronised.

Another issue is how WiB could be introduced into an existing DTT environment. Although options for transition scenarios have been identified, when WiB needs to coexist with current DTT signals, the benefits are significantly reduced, making the introduction particularly difficult.

Overall, whilst the possibility for a dramatic transmitter power reduction has been confirmed, any potential capacity gains for WiB would require further verification with detailed system implementation and planning studies. Depending on the starting scenario, implementing WiB could provide a worthwhile gain in capacity or a loss, but any gains need to be considered very carefully against the scale of the network changes required, particularly including the complexity of transition, and receiver implementations required.

## **10. Recommendations**

The mixed nature of the results from the technical studies mean that it is difficult to reach a purely technical recommendation, without further input to the discussion from the commercial group. TM-WiB is therefore not making any strong technical recommendation to TM about undertaking further work in this area and awaits guidance from the Steering Board, following further discussions in CM-WiB, TM and CM.

The work has identified some new fundamental principles and practical implementation approaches, which might be of interest to groups other than DVB, and in particular could be applicable to broadcast scenarios for hand-held reception, and so might be worthy of further study within 3GPP.

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## **Annex - details of Shannon diamond capacity calculations**

Section 3.2.2 introduced the capacity region for the case of one wanted signal and one interferer, and showed how the constraints of a broadcast network, in particular the requirement for equal bit-rate from all transmitters, lead to a limit on the capacity of the wanted signal that has the form of a “max-min” of three candidate capacities:

$$C_{pentagon} = \max\left(\min\left(\frac{C_{12,0}}{2}, C_{1,0}\right), C_{1,2}\right)$$

The notation here is  $C_{A,B}$  where  $A$  represents the signals being decoded and  $B$  represents the signals being treated as interferers. For example,  $C_{12,3}$  is the joint capacity of signals 1 and 2 in the presence of interfering signal 3. Note that this is slightly different to the notation used in section 3.2.2.

This capacity is referred to as the “Shannon pentagon” capacity in this document.

As was stated in section 3.2.5, the concept can be extended to the case of one wanted signal and two interferers. Whereas the single-interferer case had a capacity region bounded by three lines, the capacity region in the two-interferer case is bounded by seven planes corresponding seven capacity limits. These are the individual capacities ( $C_{1,0}$ ,  $C_{2,0}$ ,  $C_{3,0}$ ) of each signal if the others can be removed, the sum capacity of all three signals ( $C_{123,0}$ ), and the three pairwise sum capacities assuming the third signal can be removed ( $C_{12,0}$ ,  $C_{23,0}$ ,  $C_{13,0}$ ). The resulting three-dimensional capacity region, known as the “Shannon Diamond”, is shown in Figure 51 below. Note that the figure applies for a particular combination of received signal powers and noise level.

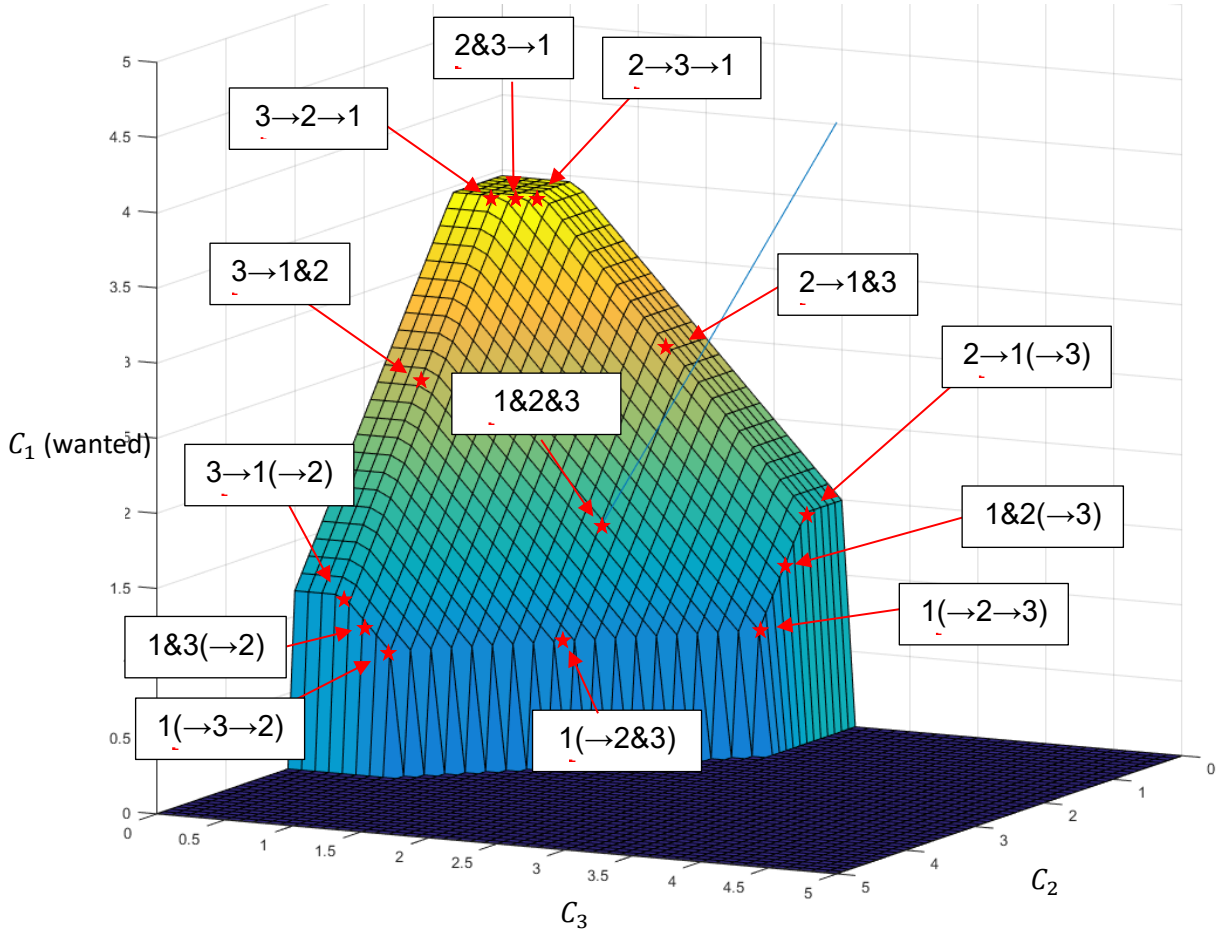


Figure 51 The three-dimensional capacity region for a wanted signal and two interferers, with the 13 possible decoding sequences

Just as there are more limits in this case, there are also more possible (hard-SIC) decoding sequences, represented by the red stars, and labelled with the decoding sequence. For example, “1&3→2” means that signals 1 and 3 are decoded jointly then they are subtracted and signal 2 is decoded.

There are 13 total decoding sequences, i.e. sequences in which all three signals are decoded: 6 three-step sequences; 3 two-step sequences of a joint decode followed by decoding the remaining signal; 3 two-step sequences of decoding a single signal followed by jointly decoding the remaining two; and one single-step sequence where all three signals are jointly decoded together.

Assuming that signal 1 is the wanted signal, this leads to 9 different capacities, shown in Figure 52 by the orange lines representing horizontal planes through the 3D volume. The 13 sequences lead to only 9 distinct capacities because three sequences (those leading to  $C_{1,0}$ ) differ only in the sequence in which the two interferers are decoded and subtracted prior to decoding the wanted signal; and another three sequences ( $C_{1,23}$ ) differ only in the sequence for decoding the interferers *after* the wanted signal has been decoded. These two triplets each collapse to a single rate for the wanted signal, hence the difference of four.

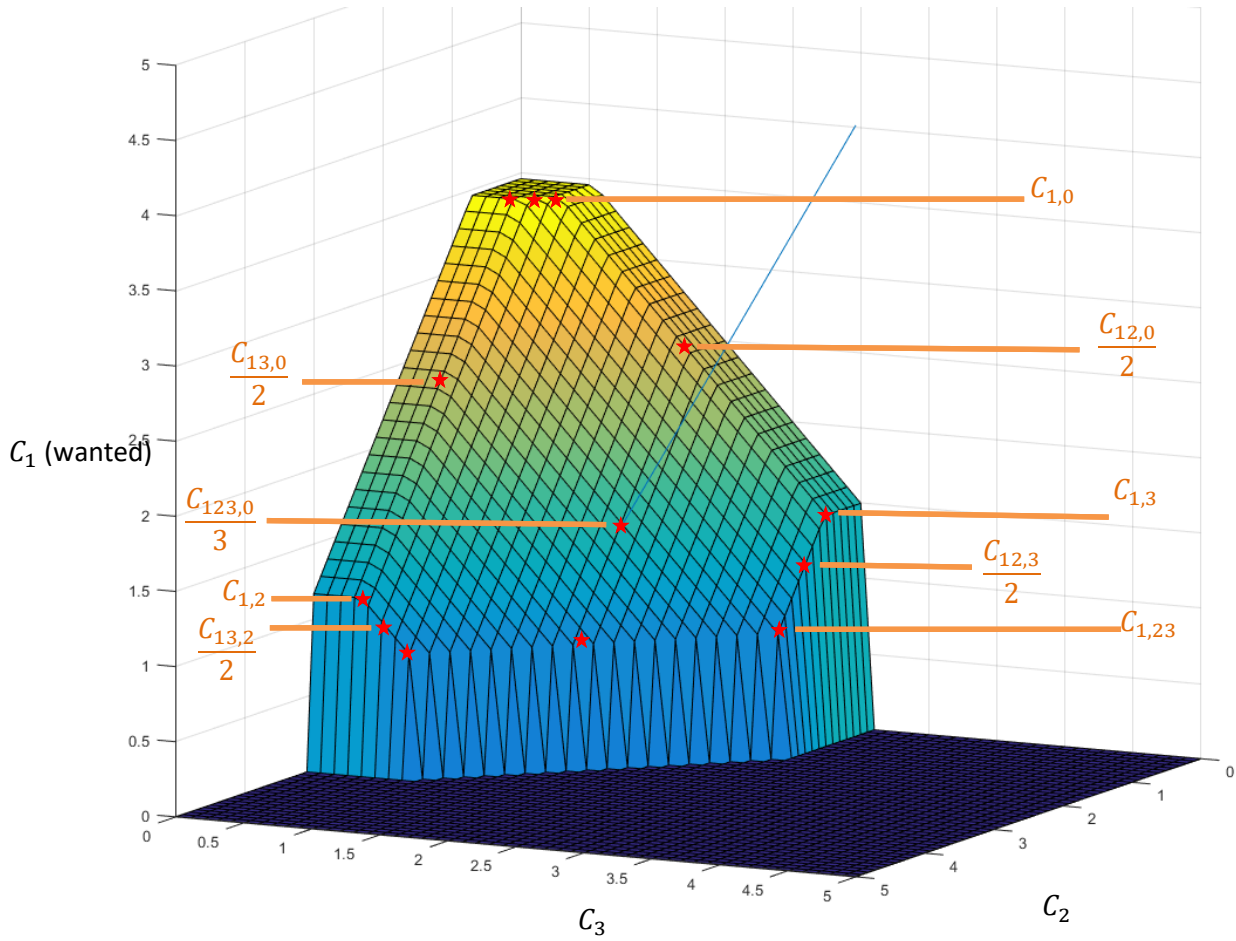


Figure 52 The nine capacities available for different decoding sequences

If decoding is assumed to stop once the wanted signal is decoded (indicated by the parentheses in the decoding sequences), then the second triplet becomes one sequence, since they are identical up to this stage, reducing the 13 total sequences to 11 truncated sequences. The members of the first triplet really correspond to different receiver behaviours, despite giving the same capacity, and would be appropriate under different circumstances.

An earlier contribution to the WiB study listed *seven* possible sequences, but these treated the two interferers as interchangeable, hence for example the sequence (2→3→1) was considered equivalent to (3→2→1).

The capacity available is the best of the following four options:

- The capacity of signal 1 treating the other two signals as interferers (i.e. what a naïve receiver would do)
- One half of the joint capacity of signals 1 and 2, treating signal 3 as an interferer, subject to the limit that this cannot exceed the capacity of signal 1 with signal 3 as an interferer
- As above but with signals 2 and 3 exchanged
- One third of the total capacity, subject to the limit that this cannot exceed
  - one half of the joint capacity of signals 1 and 2 in the presence of the noise; nor

- one half of the joint capacity of signals 1 and 3 in the presence of the noise; nor
- the capacity of signal 1 in the presence of only the noise.

The Shannon Diamond capacity is therefore:

$$C_{diamond} = \max \left\{ C_{1,23}, \min \left( \frac{C_{12,3}}{2}, C_{1,3} \right), \min \left( \frac{C_{13,2}}{2}, C_{1,2} \right), \min \left( \frac{C_{123,0}}{3}, \frac{C_{12,0}}{2}, \frac{C_{13,0}}{2}, C_{1,0} \right) \right\}$$

It might be noted that this max-min formula does not take into account any constraints on the capacities of signals other than the wanted signal, except where they appear in joint capacities together with the wanted signal. On first sight this may appear insufficient. However, it turns out that any resulting over-estimation of the joint capacity is eliminated because the corresponding argument does not “win” the “max” process.

This can be seen more easily in the 2D case of the Shannon Pentagon calculation above:

$$C_{pentagon} = \max \left( \min \left( \frac{C_{12,0}}{2}, C_{1,0} \right), C_{1,2} \right)$$

Note that here too a constraint is technically missing: in taking half the joint capacity of both signals, the capacity should be limited to  $C_{2,0}$ , the capacity due to the power of signal 2 alone, and not just to  $C_{1,0}$ , the corresponding limit for signal 1. However, by the chain rule for mutual information:

$$C_{12,0} = C_{1,2} + C_{2,0}$$

(This exact identity was derived in section 3.2.2, subject to the slight notational difference, in the explanation of why the corner points correspond to JD followed by hard-SIC).

We are concerned about the case where  $\frac{C_{12,0}}{2} > C_{2,0}$ , since this is the case in which the first argument of the “max” will overestimate the capacity available for signal 2. However, substituting for  $C_{2,0}$  in the chain rule identity:

$$\frac{C_{12,0}}{2} > C_{12,0} - C_{1,2}$$

Hence

$$C_{1,2} > \frac{C_{12,0}}{2}$$

So the second argument of the “max” will be returned and the overestimated first argument will be discarded.

Similar arguments apply to the Shannon Diamond case, though there are more cases to check and more terms in the equations. One of the participants in TM-WiB had included some of these additional constraints in their (independently derived) calculation, but analysis of the behaviour of the formula when applied to the worst point of the SFN-7 WiB network revealed that these constraints did not “bite” in any of the 10 million realisations of location variation, whereas the nine capacity constraints on the wanted signal each had many turns of being the limiting factor on capacity. This confirms that the reasoning above is correct.

A geometric interpretation is also possible:

The figures above show (in blue) the line of equal capacity  $C_1 = C_2 = C_3$ . The capacity available by doing joint decoding of all three signals, assuming equal rates from all transmitters, is given by the point at which this line crosses the boundary of the 3D capacity region. If this line crosses the sloping front facet (the one containing  $\frac{C_{123,0}}{3}$ ) then joint decoding is the best option. The other three terms in the last “min” take care of the horizontal upper face and the two sloping facets flanking the front facet.

The limits represented by the three vertical facets are *not* included in the max-min formula. However, suppose that the equal-capacity line intersects the diamond in the left-most of these facets. The point of intersection will lie on the plane  $C_1 = C_3$ , which passes through the capacity point giving  $\frac{C_{13,2}}{2}$ , and this latter point will give a better capacity for *both* signals 1 and 3 than the intersection point with the left facet. The intersection with the sloping front face will give the incorrect value, but because of the direction of slope, this point will result in a capacity for signals 1 and 3 that is *lower* than  $\frac{C_{13,2}}{2}$ . Hence the incorrect value will be discarded.

Figure 53 shows a three-dimensional contour (a MATLAB isosurface) for a capacity of 3bps/Hz. The colours indicate the applicable capacity limit in each case. All 9 limits apply at some C/I combination, as can be seen more clearly in the top view in Figure 54.

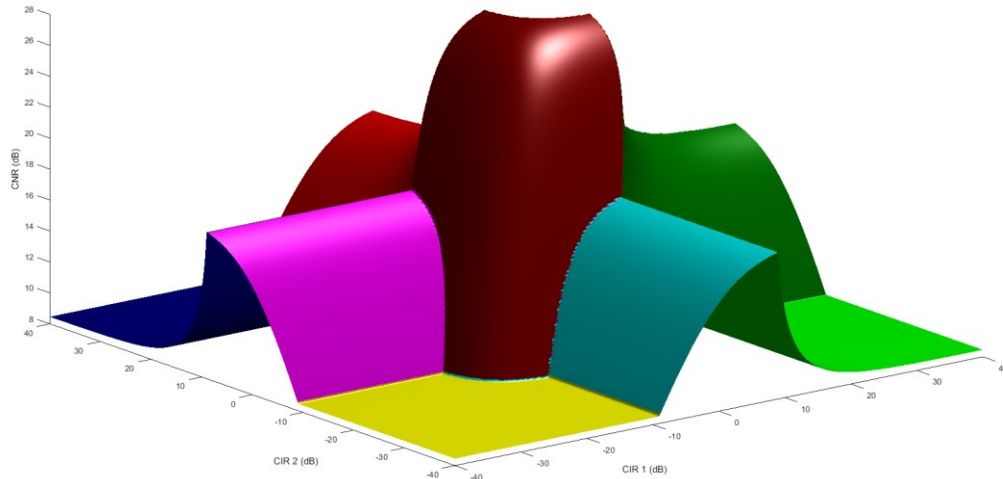


Figure 53 Contour of 3 bit/s/Hz for the Shannon Diamond capacity



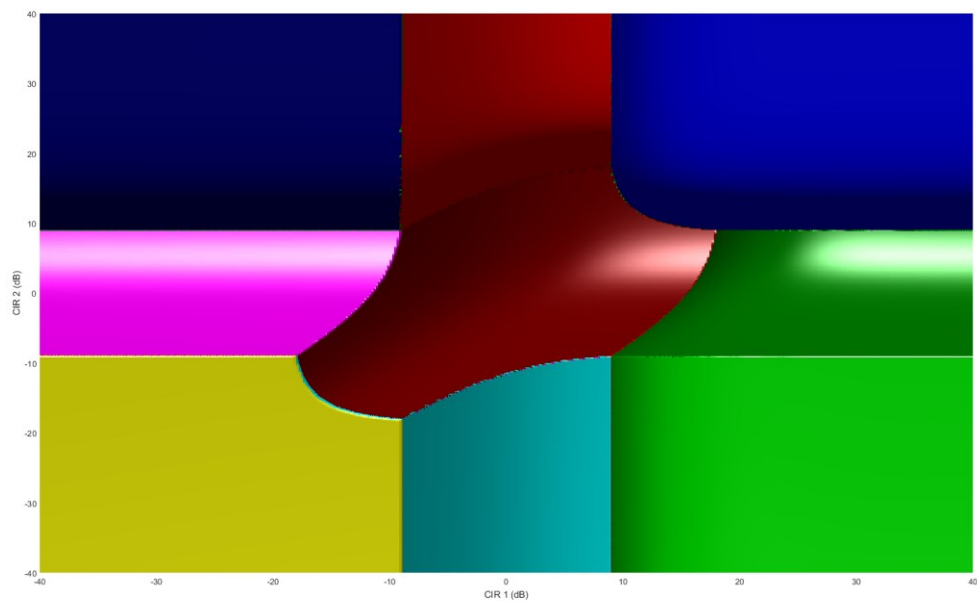


Figure 54 Top view of the 3bit/s/Hz capacity contour showing the regions in which the nine capacity limits apply