Service Recommendations to Support Technology Neutral Allocations

FDD/TDD Coexistence

10 April 2007

Executive Summary

Technology-neutral licensing of broadband wireless technologies such as WiMAX™ technology has the potential to facilitate technology growth and to enable market mechanisms to drive the adoption of spectrally efficient and economically efficient radio technologies. However, since different operators in adjacent bands might choose to use differing technologies, the coexistence of technologies is a fundamental concern; when transmitters and receivers are operating simultaneously in adjacent spectrum and in close proximity, the transmitters may cause significant interference to the receiving systems. One special case in which the interference paths are not mutual is the coexistence of frequency division duplex (FDD) systems, which operate in paired spectrum, with time division duplex (TDD) systems.

In Figure A, we show a typical band structure with FDD uplink (UL) and downlink (DL) at either end of the band, sandwiching an unpaired band assigned to TDD systems. The green and blue paths on the diagram indicate wanted UL and DL signal paths, respectively. The yellow paths indicate mobile station to base station interference in the FDD uplink band; base station to mobile station interference in the FDD downlink band; and interference in both directions in the TDD band. These forms of interference are relatively benign, as good separation can usually be maintained. Nevertheless, so-called 'dead zones' may be created around the base stations of the interfering network. Various mitigation techniques exist, however, such as the collocation of base station sites. More serious are the base station to base station and mobile station to mobile station interference paths.

In the case of TDD systems these interference paths may be removed by synchronising uplink and downlink transmissions in adjacent channels, furthermore, the interference is mutual (as indicated by the double headed orange arrows). Thus resolving any interference issues will typically benefit both operators and so there is an incentive for operators to cooperate.

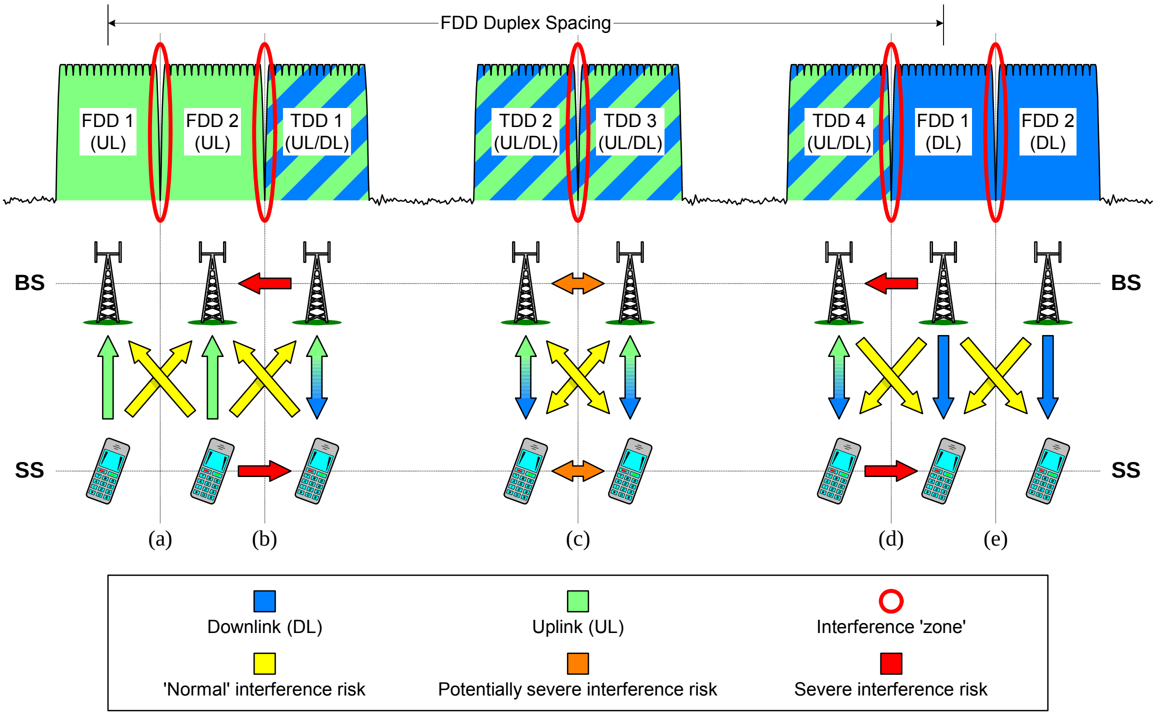

Figure A The sources of adjacent channel interference for the various FDD/TDD coexistence scenarios.

The most serious interference paths are between FDD and TDD systems and *vice versa* (shown in red), in which the interference is unidirectional, i.e. the operator of the interfering network has no incentive to help resolve interference issues experienced by the victim network. For FDD uplink adjacent to a TDD channel, the FDD base station suffers interference from the TDD base station, whereas the TDD mobile, as well as the base station suffers interference from the FDD mobile station. Similarly, for FDD downlink adjacent to a TDD channel, the TDD base station and the TDD mobile station suffer interference from the FDD base station, whereas the FDD mobile station suffers interference from TDD base stations and mobile stations. Since base stations tend to have high transmit powers, sensitive receivers with high gain antennas and are frequently in line-of-sight, interference between them can be very serious. Simply collocating base stations to alleviate base-to-mobile interference will exacerbate base station-to-base station interference so other solutions need to be found to enable efficient use of spectrum.

In bands such as the 3.4-3.8 GHz band, technology-neutral paired allocations are made, and should a paired allocation be used for TDD, the corresponding channels in the lower and upper bands have the same licencees in the adjacent channels. In this case, FDD and TDD operators do have an incentive to cooperate to resolve interference as, for example, if there is significant FDD base station-to-TDD base station interference one band there is likely to be significant TDD base station-to-FDD base station interference in the other band.

There are technology factors that can affect coexistence that arise in the transmitter, e.g. out-of-band and spurious emission levels, linearity and filtering, while further factors exist in the victim receiver, e.g. selectivity and blocking. Since the interference is a function of both, achievable receiver performance should be considered when setting transmitter performance specifications. Other considerations that affect the consequences of interference include antenna discrimination (including the use of so-called ‘smart’, i.e. adaptive, antennas) and active interference cancellation techniques.

Deployment strategies can also affect coexistence and mitigation techniques include the use of physical separation, site features for shielding and cooperation and coordination between operators.

Regulation should specify appropriate limits for transmit powers and out-of-band emissions.

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List of Abbreviations

AAS	Adaptive antenna systems
ACLR	Adjacent channel leakage ratio
ACIR	Adjacent channel interference ratio
ACP	Adjacent channel protection
ACS	Adjacent channel selectivity
BS	Base station
BRS	Broadband radio services
CFR	Code of Federal Regulations
DECT	Digitally enhanced cordless telecommunications
DL	Downlink
DSP	Digital signal processing
EBS	Educational broadband services
FCC	Federal Communications Commission
FDD	Frequency division duplex
GMSK	Gaussian minimum shift keying
HFDD	Half frequency division duplex
IMP	Intermodulation product
LOS	Line-of-sight
MAC	Medium access control
OFDM	Orthogonal frequency division multiplexing
OOBE	Out-of-band emissions
PA	Power amplifier
PAPR	Peak-to-average power ratio
PHY	Physical layer
RF	Radio frequency

SIR	Signal-to-interference ratio
SS	Subscriber station
TDD	Time division duplex
TDMA	Time division multiple access
UL	Uplink
UNII	Unlicensed national information infrastructure

1 Introduction

With the onset of new broadband wireless technologies such as WiMAX™ technology, technology neutral assignments are increasingly being considered (and indeed required) to facilitate technology growth and deployment. Regulators across the globe are recognising the importance of technology neutrality. However, they are faced with new questions regarding the ability of technologies with different characteristics to coexist in shared frequency bands.

One of the main considerations to promote coexistence is to address the needs of differing duplex methods, namely, time division duplex (TDD) or frequency division duplex (FDD). Unchecked, operating systems with differing duplex methods in close proximity to one another may cause unacceptable levels of inter-system interference, when the base stations and terminals have very different characteristics.

Various interference mitigation techniques are available that may be used to allow a mixture of FDD and TDD systems to coexist. This document describes these techniques (primarily in the context of WiMAX technology) and discusses how technology neutral deployments may be realised successfully in the future. It is important to note that the contents of this document are only intended to provide a guideline since geo-regulatory and spectrum variations mean that each usage scenario is likely to be different and unique both in terms of equipment and deployment.

In Section 2 we introduce WiMAX systems and describe the duplex methods that represent one of the key factors distinguishing the various ‘flavours’ of the technology. Then we consider the main coexistence scenarios and the factors relevant to the performance in each scenario. The need for FDD and TDD systems to coexist in adjacent spectral bands is not a new requirement, and neither is it specific to WiMAX technology. Section 3 summarises the main findings of a literature search into the subject. In Section 4 we discuss regulatory matters that may need to be considered if FDD and TDD variants of WiMAX technology are deployed into a common band. Finally, in Section 5 the main findings are concluded.

2 WiMAX Technology and the Coexistence of FDD/TDD Systems

We begin by introducing WiMAX technology and then consider the various coexistence scenarios that may be envisaged, with a view to identifying the various interference 'paths' that may result. We conclude this section by considering the factors that may affect performance in the coexistence scenarios identified.

2.1 WiMAX Technology Overview

WiMAX is an emerging standards-based broadband wireless technology that defines the physical (PHY) and medium access control (MAC) layers. The standards upon which WiMAX technology is based are the IEEE 802.16 standards, which are large, complex standards with many possible configurations and non-mandatory options. This means that differing equipment that is 802.16-compliant is not necessarily compatible. WiMAX technology addresses this problem by defining 'system' profiles that define allowed modes of operation and specifying mandatory options. These options are then specified to greater detail, e.g. specifying frequency, duplex method, etc, in the form of 'certification' profiles. Thus equipment conforming to a particular certification profile should be interoperable, regardless of vendor.

Currently two system profiles are defined. 'Fixed WiMAX™' is based on the IEEE 802.16-2004 standard and is intended primarily for the implementation of fixed, high bandwidth wireless links with low transceiver complexity. 'Mobile WiMAX™' is based on the 802.16e-2005 amendment to the 802.16-2004 standard and is designed to support mobile applications, with improved robustness in a mobile, time varying radio channel. In the future, a third system profile, 'evolutionary' WiMAX is likely to be defined. Fixed WiMAX currently has both FDD and TDD certification profiles. Certification profiles for Mobile WiMAX are currently only defined for TDD modes of operation.

The characteristics of WiMAX technology make it an ideal contender for a number of 'modern' applications. These include 'last mile' broadband connections, broadband hotspots, cellular backhaul and high-speed enterprise connectivity for business.

2.2 Duplex Methods

In the majority of point-to-point wireless communication applications, full duplex operation is required, i.e. the flow of data needs to be bi-directional. (There are of course some point-to-point and point-to-multipoint applications when only unidirectional, simplex operation is required, e.g. radio and TV broadcast). Therefore, most radio technologies require a method to support the transfer of data in both directions. There are three main duplex methods used in digital wireless systems, namely time division duplex (TDD), frequency division duplex (FDD) and half frequency division duplex (HFDD). These duplex methods are illustrated in Figure 1 and discussed in the following sections.

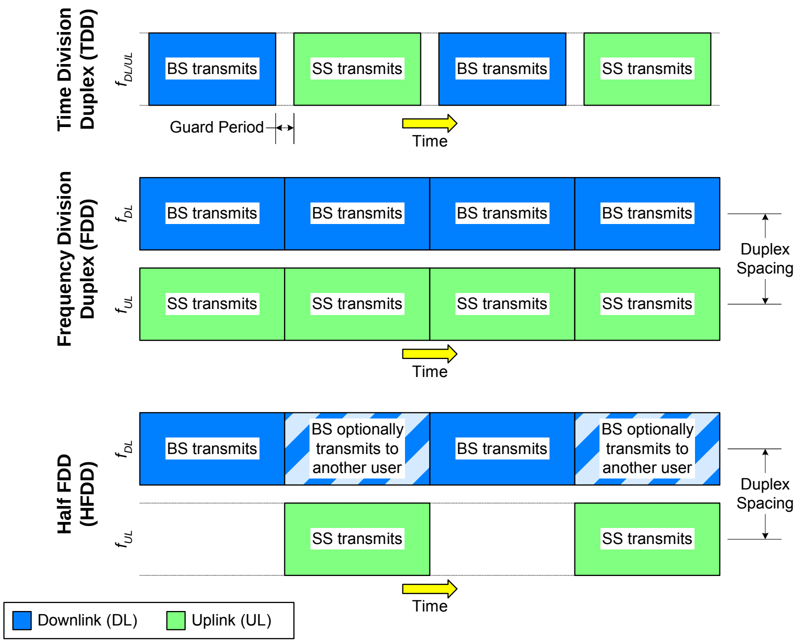

Figure 1 The three main types of duplex technology used in wireless systems, time division duplex (top), frequency division duplex (middle) and half frequency division duplex (bottom), which is a special form of FDD.

The selection of a duplex method is based on technology and regulatory considerations that are beyond the scope of this document. However it is sufficient to say that the arguments to use FDD in preference to TDD and *vice versa* are similar to those of existing cellular mobile radio technologies.

2.2.1 Time Division Duplex

TDD, shown in Figure 1 (top), is a technique whereby information is transmitted and received using a common frequency band but at different times. Thus by reusing a single frequency band for both uplink (UL) and downlink (DL) transmissions, TDD operation typically only requires a single band of frequencies. This means that TDD systems can be deployed in paired and unpaired spectrum. Note that this ability to operate in unpaired spectrum means that TDD is favoured by unlicensed radio products, eg, the unlicensed national information infrastructure (UNII) bands in the USA, digitally enhanced cordless telecommunications (DECT) equipment and WiFi. Nevertheless, FDD and TDD systems are used in licensed and unlicensed spectrum.

TDD has the potential to offer improved spectral efficiency over FDD in applications where the data bandwidth required on the UL and DL is asymmetrical and time variant. In a basic TDD system the proportion of time allocated to the UL and DL transmissions is fixed. However, in more advanced TDD systems, it is possible to adapt the timing of the physical layer to share the available bandwidth between the UL and DL dynamically. This ability to adapt the characteristics of the physical layer to the traffic requirements of the user can be used to increase capacity and/or improve perceived data throughput. This concept is not without complications, however. Using a dynamic rather than fixed timing structure does come at the expense of increased system complexity. Moreover, there are advantages to a fixed timing structure because, as will be discussed in greater detail later on, a fixed timing structure permits different systems to be synchronised to mitigate against adjacent channel interference issues. Note that WiMAX systems support adaptive transmission timing for TDD transmissions.

In a point-to-multipoint TDD system the subscriber stations[1] (SSs) will typically adjust their transmit timing so that the signals arriving at the base station (BS) are aligned with the BS's timing structure. Despite this, however, it is necessary to

[1] Other widely recognised terms for subscriber station are mobile station (MS), user equipment (UE) and customer premises equipment (CPE), depending on the application.

introduce 'guard' periods between UL and DL transmissions to prevent collisions and to allow the transceiver equipment to switch from transmit to receive mode and *vice versa*. Note that abrupt changes in output power can result in significant wideband emissions. Therefore, TDD transmitters typically have to ramp their output power up and down in a controlled manner. These ramp up and ramp down periods are part of the switching time and must be taken into account when deciding the duration of the guard periods. Another factor that has to be taken into account when considering TDD operation is round trip delay time. Radio waves propagate approximately 300 m every microsecond. Thus as the separation between the BS and SS increases, the minimum time allowed between transmit and receive packets increases also. This potentially affects the size of the guard periods and/or imposes a maximum link distance. Note that round trip delay issues are typically mitigated to a certain extent in time division multiple access (TDMA) systems by interleaving transmissions to/from the various users.

Increasing the size of the guard periods allows the timing requirements (i.e. switching time and timing adjust capabilities) of the transceiver equipment to be relaxed. However, no useful data can be transmitted during the guard periods so increasing the size of the guard periods reduces the spectral efficiency of a system.

2.2.2 Frequency Division Duplex

FDD, shown in Figure 1 (middle), is a technique whereby information is transmitted and received using different frequency bands. The separation between the UL and DL frequencies is referred to as the 'duplex spacing'. Generally, but not always, for any given frequency plan the duplex separation is fixed leading to an ordered arrangement of paired channels in two sub-bands.

Typically FDD sub-bands are identified explicitly for UL and DL transmissions, with the DL typically assigned to the higher frequency band in most existing cellular radio systems. FDD systems require the use of paired spectrum. To this end, spectrum licenses are generally granted in pairs. The duplex spacing, i.e. the separation between UL and DL frequency bands is typically several tens of MHz. This minimum separation functions as a guard band to prevent UL/DL interference. Most cellular systems employ FDD and spectrum is commonly licensed for FDD operation, eg, 3.5 GHz in Europe, 1.9 GHz in North America and 2 GHz in Japan.

FDD is less well suited to operation in unlicensed spectrum than TDD. With a TDD system it is only necessary to find a single band of unused spectrum. With FDD two bands are required. Clearly it is easier to find a single band than two! If the duplex spacing could be adjusted dynamically then the task of finding available spectrum might be easier. However, the consequence of a variable duplex spacing is an increase in the complexity of the terminals and filtering requirements together with the need for signalling the appropriate spacing. Furthermore, the duplexing filter is fixed at the time of manufacture, although there has been research into switchable and tuneable filters.

Whereas TDD systems have the potential to adapt their transmission timing to offer asymmetrical data links (and hence improve spectral efficiency when symmetrical data links are not required) there is no such option in an FDD system. In an FDD system the frequency bands and hence useable bandwidth are predefined separately for the DL and UL. Whilst traditional wireless applications such as voice services are well suited to symmetrical data links, newer applications such as web browsing and video on demand often require more bandwidth on the DL. Recent FDD technologies, eg, third generation technologies tend to have significantly greater downlink efficiencies compared with their uplink efficiencies, in part because throughput needs to be greater on the downlink, and the same bandwidth is available. Therefore, TDD systems are more suited for asymmetrical data traffic, which can improve spectrum efficiency for data services.

2.2.3 Half Frequency Division Duplex

HFDD, shown in Figure 1 (bottom), is a special case of FDD. In FDD BS equipment a special filter or 'duplexer' is used to allow the BS to transmit and receive on different frequencies simultaneously without significant power from the transmitter leaking into the receive path and 'blocking' the receiver.

High-performance duplexers are often quite bulky, expensive and are optimised for operation with predefined frequency bands. Considering the ever present requirements to minimise cost and weight in high-volume, entry-level mobile handsets, having to integrate a duplexer into SS equipment is not desirable. HFDD addresses this issue by operating a TDD-style transmit and receive timing structure. Thus the timing can be arranged such that the SS never has to simultaneously transmit and receive, which means that the duplexer can be replaced by a simple low-cost radio frequency (RF) switch.

HFDD basically represents a limitation imposed by the SS on the timing of the DL and UL transmissions. BS equipment would generally use a duplexer and support full FDD (to only transmit half the time on two frequency bands would be very inefficient and would not normally be done). Thus the BS can support two SSs using HFDD by transmitting to SS A whilst receiving from SS B.

Examples of successful technologies that use HFDD include GSM and TETRA.

2.2.4 WiMAX Profiles and Defined Duplex Methods

WiMAX certification profiles based on the IEEE 802.16 family of standards are in development to support TDD, FDD and HFDD modes of operation. The choice of duplex method mainly affects the RF channel bandwidth and frame length required. In WiMAX systems, the implementation of the duplex method is handled at the physical layer (PHY).

Currently, Fixed WiMAX profiles exist for both TDD and FDD modes of operation. The certification profiles for Mobile WiMAX, which is based on 802.16e, will predominately specify the TDD duplex method.

2.3 Flexible Usage Regulations Benefits and Challenges

Traditionally, licensed (and indeed some unlicensed) spectrum has been allocated via strict command and control methods, i.e. spectrum access has been controlled by a central regulatory body. Typically, as well as deciding who may operate in any given frequency band, the regulator has also dictated which radio technologies may be used and for what purpose. Globally, there is an ever increasing desire to move away from command and control methods towards spectrum trading, i.e. where the regulator takes a back seat and allows operators to trade spectrum freely between themselves, and spectrum liberalisation, i.e. where restrictions on technology and service type are relaxed. Both concepts aim to promote more efficient spectrum utilisation; first by placing financial value on spectral resources and then by allowing operators to deploy more spectrally efficient technologies in order to reduce their spectral needs. The potential benefits of spectrum trading and liberalisation are clear. However these concepts, specifically allowing different radio technologies to operate in adjacent spectrum, also bring significant challenges.

Of particular concern is the ability of FDD and TDD systems, e.g. different WiMAX variants, to coexist. Opening spectrum access to allow these systems to coexist has been difficult to realise, especially in some regions where the many potential national and licence boundaries have lead to a perception that TDD operation can bring coordination problems. There is growing interest in TDD operation, which has led to a number of studies that have looked at the challenges and solutions in considerable detail (these are discussed later in Section 3). A key aspect of these studies has been the realisation that no matter what techniques are employed, it is impossible to guarantee there will never be any interference challenges but that there are many considerations and measures that can be applied to manage and mitigate the problems in any given deployment scenario.

With the understanding that interference mitigation techniques are available, regulations are becoming more flexible and mixed TDD and FDD operation is widely anticipated. In some cases this can be seen with separate frequency blocks identified for TDD and FDD systems. However there are other examples where paired frequency blocks have been identified without any assumption made regarding the duplex method that should be deployed. Furthermore, there are examples of complete flexibility whereby even the FDD duplex spacing remains unspecified in the regulatory frequency plans. In the latter two examples, technology neutral measures like block edge emission masks are proposed to control the amount of interference into adjacent frequency blocks. These represent a compromise between a tolerable and manageable level of potential interference against the extra constraints and requirements on the in-block equipment operating near the block edge. Allocating contiguous blocks to operators minimises the numbers of block edges, and allows greater flexibility in filtering and mitigation, e.g. imposing internal guardbands and therefore contiguous allocations are recommended.

Finally there are examples where regulation has mandated specific guard frequencies between blocks. This approach can reduce technological neutrality and is less flexible in accounting for the specifics of equipment characteristics and deployment scenarios. Moreover, enforcing mandatory guard bands implies reduced spectrum utilisation as guard bands may prohibit the deployment of solutions that are compatible with the technologies deployed on either side. Whilst such solutions are likely to be sub-optimal in terms of outright spectral efficiency, there are clearly advantages in allowing some traffic to be carried in the 'guard frequency' bands.

As an example of how guard frequency bands may be utilised consider a frequency band in which operators want to deploy both TDD and FDD variants of WiMAX technology. Mixing TDD and FDD systems is quite a challenging coexistence scenario. A 'safe' approach would be to rule that one or more channels be left unused between the TDD and FDD systems in order to ensure that there are no serious interference issues. Thus these channels can not be used to carry any traffic which implies poor overall spectrum efficiency. A more effective solution would be to deploy a FDD WiMAX system in these guard channels and configure both UL and DL for HFDD operation (typically HFDD is only used on the UL as described in Section 2.2.3) and synchronise the timing to that of the TDD system. Thus from the perspective of the TDD network the HFDD system appears as another TDD system with synchronised timing to prevent blocking during the receive phase. From the perspective of the FDD network the HFDD system appears as a FDD system so again blocking problems are avoided. At first glance configuring a FDD network to use HFDD on both the UL and DL would appear inefficient, which is correct because the spectrum is at most 50% utilised. However, achieving 50% utilisation is clearly much better than 0% utilisation which is the case when all operation in the guard bands is prohibited.

2.4 Coexistence Scenarios

As discussed in Section 2.2, wireless radio technologies can use different methods to implement full duplex communications. When similar systems are deployed by different and competing operators in close proximity there are various system planning challenges that have to be addressed. When systems operating different duplex methods are deployed additional challenges may be introduced.

The network planner has a wide ranging ‘toolbox’ of techniques that may be used to help mitigate inter-technology and inter-network interference problems. These are discussed in greater detail in later sections of this report. First, however, it is necessary to identify the coexistence scenarios that might be encountered if TDD and FDD variants of WiMAX technology (and indeed any other wireless technology) are deployed in adjacent frequency bands. Figure 2 shows the five adjacent channel coexistence scenarios that would be possible if TDD and FDD variants of WiMAX systems were deployed within a single frequency band. UL and DL transmissions are identified by the green and blue arrows, respectively. Fundamentally, interference problems may occur if equipment on one frequency is trying to receive whilst nearby equipment on an adjacent frequency is transmitting. In each scenario there are four paths to be considered, namely, BS-to-BS, BS-to-SS, SS-to-BS and SS-to-SS. The potential interference paths are identified with the yellow, orange and red arrows, where the colour represents the potential risk/severity of interference related issues. Each scenario is discussed in greater depth in the following sections.

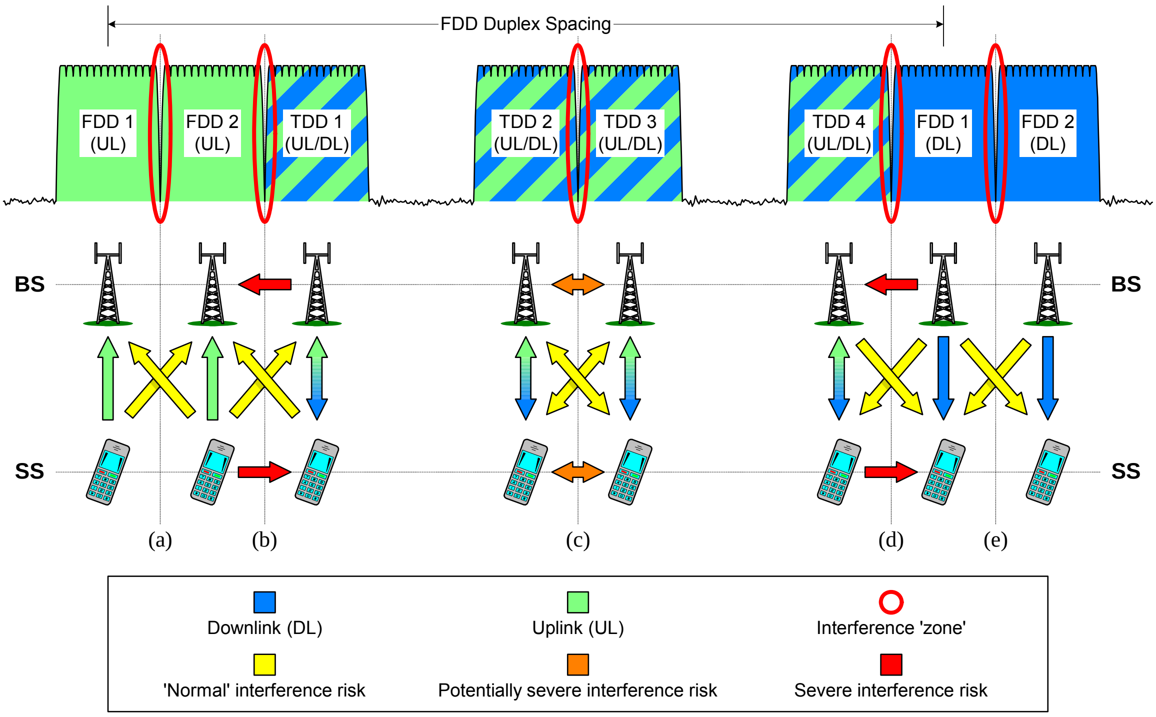

Figure 2 The sources of adjacent channel interference for the various FDD/TDD coexistence scenarios.

2.4.1 FDD-FDD

The first coexistence scenario is FDD-FDD. There will typically be two interference 'zones'. These are between adjacent UL frequencies (as shown in Figure 2 (a)) and between adjacent DL frequencies (as shown in Figure 2 (e)). Note that for the purposes of this discussion we will assume that there is always a sufficient guard band between UL and DL frequencies so that interaction between the two is negligible. This assumption is typically valid in multi-licensee scenarios, in which the DL and UL frequencies tend to grouped and ordered consistently.

As stated above, adjacent channel interference problems may occur if equipment on one frequency is trying to receive whilst nearby equipment on an adjacent frequency is transmitting. Therefore for the FDD-FDD coexistence scenario the primary interference paths are SS-to-BS on the UL and BS-to-SS on the DL; BS-to-BS and SS-to-SS interference will not generally be significant.

A scenario in which BS-to-SS interference on the DL can become problematic is shown in Figure 3 (top). Here, two adjacent channel BSs are positioned to cover a particular region. The BSs are operated by competing operators and are positioned independently. When operating close to their BS, SSs from Network A receive with very good signal-to-interference ratio (SIR). However, as SSs from Network A move towards Network B's BS, adjacent channel interference levels rise significantly as the signal level from BS A drops and the adjacent channel interference power from BS B increases.

The problems observed in the above scenario can be alleviated by encouraging operators to collocate BS equipment at shared locations. This is shown for our example in Figure 3 (bottom). Now both BSs are 'looking' in the same direction and adjacent channel interference levels are bilaterally more uniform across the entire coverage region, which should lead to more deterministic, reliable coverage for *both* operators.

A similar scenario to the above example can occur on the UL; a SS that is transmitting at a high power to communicate with a distant BS can cause significant adjacent channel interference if in the vicinity of an adjacent channel BS. Again, this so-called 'near/far' problem is improved when BSs are collocated.

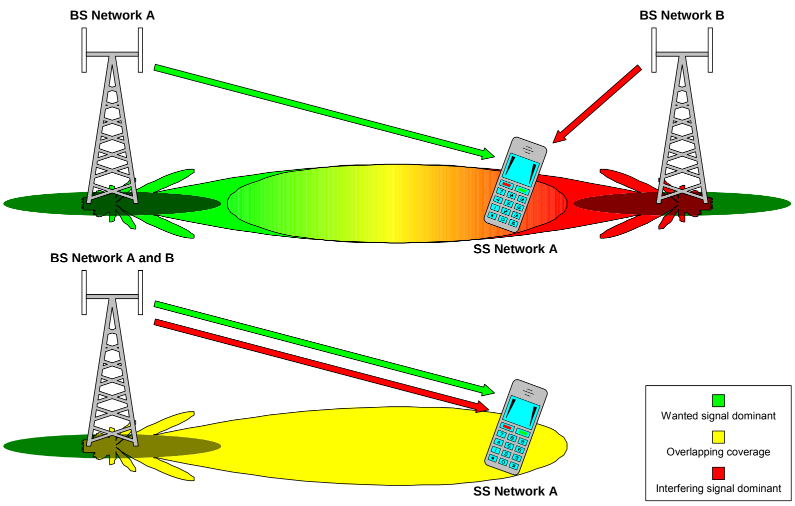

Figure 3 Collocating BSs to mitigate adjacent-channel interference.

A final note on the FDD-FDD coexistence scenario is that if a consistent DL/UL plan is not in place, i.e. the UL and DL frequencies are not grouped together and separated from each other or arbitrary duplex spacings are adopted, then frequency discrimination between UL and DL transmissions can no longer be ensured, particularly if an UL channel were adjacent to a DL channel, and the interference scenario tends towards that of the FDD-TDD scenario, discussed in the following section.

2.4.2 FDD-TDD

The second coexistence scenario is FDD-TDD. Again there are two interference 'zones', i.e. a TDD system operating in the band adjacent to the UL (as shown in Figure 2 (b)) and a TDD system operating in the band adjacent to the DL (as shown in Figure 2 (d)). The most obvious difference between this and the previous scenario is that frequency discrimination cannot be relied upon to isolate the UL and DL. This scenario includes the same interference paths found in the FDD-FDD scenario *plus* potentially crippling BS-to-BS and SS-to-SS interference paths between the systems. These paths are identified in Figure 2.

SS-to-SS problems are caused when one SS is transmitting in the close proximity of another receiving in the adjacent channel. When the TDD system operates in a channel adjacent to the FDD UL, the TDD SS suffers interference from the FDD SS, but not necessarily *vice versa*, while if the TDD system operates in a channel adjacent to the FDD DL, the FDD SS suffers interference from the TDD SS, but not necessarily *vice versa.* In general, if the SSs are operated close enough to one another there is nothing that can be done to mitigate this problem. However, we note that affected SSs will generally be mobile so a) the problem will only continue whilst the SSs are close together and b) the number of users affected by the problem is minimal. Furthermore, the severity of the problem is a function of the transmit power of the SSs and the level of cochannel interference received. Therefore we will not consider this interference path further in this section.

BS-to-BS interference affects the FDD system on the UL and TDD systems adjacent to the FDD DL band. Again this is caused when one BS transmits whilst the other receives on the adjacent channel. Unlike the SS-to-SS case, BS-to-BS interference is more deterministic (i.e. it will typically be a problem or it won't), as BSs are active continuously and they do not generally move. However, BS-to-BS interference potentially affects all cell users and will typically be more serious than SS-to-SS interference.

In the previous scenario we noted that collocation of BS equipment may be used to mitigate against the main source of adjacent channel interference issues in the FDD-FDD scenario. This approach is still applicable when considering BS-to-SS and SS-to-BS interference issues, in the FDD-TDD case. However, without additional measures, simply collocating BS equipment could make BS-to-BS problems worse due to the close proximity (and hence low isolation) of the antenna systems. Solutions that may be applied include the use of higher performance analogue transmit/receive filters (although this can only achieve so much when considering systems operating very close together in frequency because the filters still have to pass the wanted signals without significant distortion or attenuation). Another solution is to use available structures (either man-made or natural) and intelligent antenna selection and positioning to minimise the coupling between the various antenna systems. Examples include using directional antennas with vertical separation and using a building's structure to shield one antenna from the other. These mitigation approaches and others will be described in Section 2.5.

2.4.3 TDD-TDD

The final coexistence scenario is TDD-TDD, shown in Figure 2 (c). The TDD-TDD scenario is very similar to that of the FDD-TDD scenario and solutions for the latter are also applicable to the former. There is, however, an additional interference mitigation method that can be applied in the TDD-TDD scenario to virtually eliminate BS-to-BS and SS-to-SS interference issues.

As discussed in Section 2.2.1, TDD systems alternate between transmit and receive modes. Moreover, as mentioned previously, interference problems exist when one entity is trying to receive whilst another transmits. Therefore, if the transmit and receive timing of adjacent channel TDD systems could be synchronised, eg, to GPS, with the same frame structure, the most significant interference paths can be eliminated. This is shown in Figure 4, using BS-to-BS interference as an example.

With unsynchronised BSs (as shown in Figure 4 (top)) transmissions from one BS can desensitise the receive path of another. Synchronising the timing of the transmit and receive windows (as shown in Figure 4 (middle)) eliminates this problem. Note that, however, this only works if all systems use a common transmit/receive timing structure; if the timing is adapted to the bandwidth requirements then it becomes virtually impossible to avoid contention (as shown in Figure 4 (bottom)).

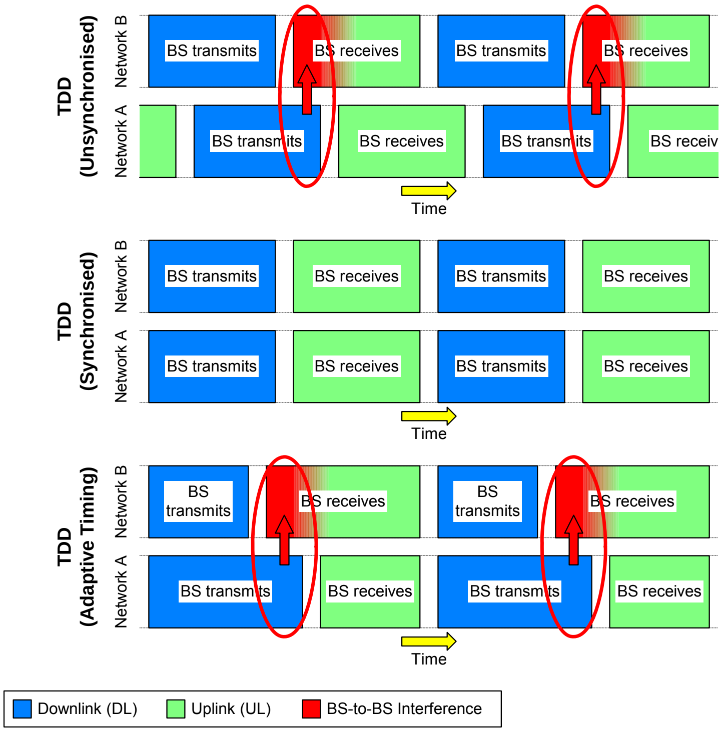

Figure 4 Synchronising TDD systems to mitigate BS-to-BS (and SS-to-SS) interference (top and middle). The scope for synchronising systems with adaptive timing is limited (bottom).

2.5 Factors Affecting Coexistence

In the previous sections we have used our knowledge of the various duplex methods (described in Section 2.2) to consider the potential interference paths in the main coexistence scenarios. Thus the paths of interest have been identified. However, in order to be able to evaluate possible mitigation techniques, we need to understand which factors may affect the ability of two systems to coexist in adjacent frequency bands. These factors can be split into so-called 'technology' factors, i.e. factors related to the radio equipment itself and 'deployment' factors, i.e. factors related to the wide-area planning and deployment of equipment. We consider each of these in turn in the following sections.

2.5.1 Technology Factors

There are a number of factors related to the radio equipment that may affect performance in a coexistence scenario. The key factors are as follows:

- *Transmitter out of band and spurious emission levels*

  The first source of adjacent channel interference is out-of-band emissions (OOBE) and spurious signals generated by the transmitter. Ideally, 100% of the power output by the transmitter will be contained 'in band'. However, in reality this is not practical due to the limitations of realisable filters and the non-ideal characteristics, e.g. nonlinearities, of components used in the construction of the transmitter. OOBE generally refers to power measured over a predefined bandwidth whereas spurious emissions refer to the power of persistent unwanted spectral components.

  OOBE and out-of-band spurious emissions from a transmitter operating on one network may represent in band interference to a receiver operating on another network. Even with an 'ideal' receive filter a receiver cannot suppress this kind of interference. An example is shown in Figure 5. In Figure 5 (top), a signal is transmitted with significant OOBE. At the receiver some of the power from the transmitted signal passes through the receiver filter, as shown in Figure 5 (middle). This power will reduce the SIR for wanted signals and hence reduce the sensitivity of the receiver.

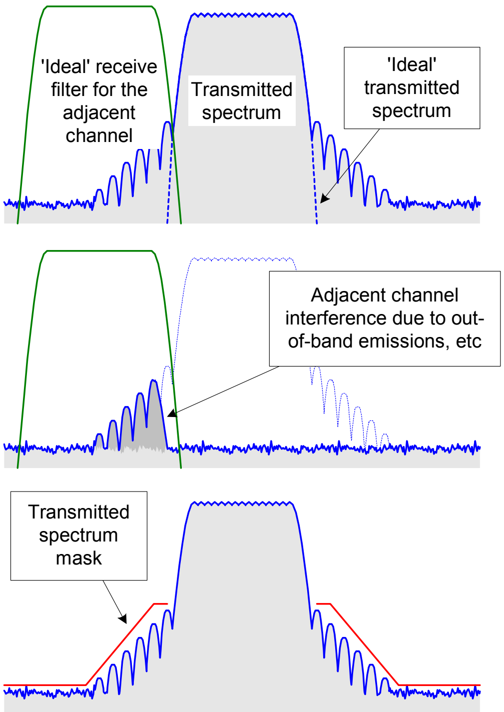

Figure 5 Interference caused by out-of-band emissions (top and middle) and the use of spectral masks for transmitter conformance (bottom).

To keep problems related to OOBE and spurious emissions to manageable levels, most radio standards impose strict spectral masks for the transmitter, as shown in Figure 5 (bottom). By ensuring that all equipment conforms to these masks, network planners can assume worst case scenarios when analysing the possible impact of interferers operating in adjacent channels. It is possible that more stringent transmission masks may be imposed on equipment that will be operated 'next to' unlike equipment.

As an example, OOBE for a typical FDD or TDD transmitter may be, say, -30 dBc in the first adjacent channel and -50 dBc in the second adjacent channel [1]. Adding a relatively low cost, band pass cavity filter may improve these figures by 15 and 40 dB, respectively. Thus a transmitter with even basic filtering should be able to suppress OOBE below -45 dBc in the first adjacent channel and -90 dBc in the second adjacent channel.

A typical measure of OOBE and spurious emissions is adjacent channel leakage ratio (ACLR), which is measures OOBE in the adjacent channel with respect to the power of the 'main', i.e. wanted, signal.

- *Transmitter linearity*

As stated above, one factor that may contribute to OOBE is the filter characteristics achievable with practical filters (especially when considering filters in SSs). Another significant contributor is system nonlinearities and power amplifier (PA) nonlinearity in particular.

Minimising power consumption is often a key requirement in any wireless transmitter and the PA is often one of the most power-hungry elements in a transmitter. Although highly efficient, nonlinear PAs may be used with constant-envelope modulation schemes such as Gaussian minimum shift keying (GMSK), linear modulation schemes such as orthogonal frequency division multiplexing (OFDM) require the use of less-efficient, linear PAs. Even 'linear' PAs will exhibit nonlinear behaviour if driven hard enough. Therefore it is typically necessary to 'back off' the output power of a linear PA to keep any nonlinearities to acceptable levels, which further reduces PA efficiency. Some of these problems may be mitigated by linearization techniques that may be used to improve the efficiency, but even these have limitations, as will be described later. Therefore a compromise must be struck to trade power consumption against nonlinearity and the resulting OOBE.

A simple example showing the potential effects of a nonlinear transmit path is shown in Figure 6. Figure 6 (top) shows the spectrum of an 'ideal' 2048-carrier OFDM signal; no significant out-of-band power is present. In Figure 6 (bottom) then same signal is augmented with a third-order component to represent the behaviour of a PA with a nonlinear characteristic. The resulting third-order intermodulation products (IMPs) have resulted in significant OOBE, which may represent significant interference power to users operating in the adjacent channels.

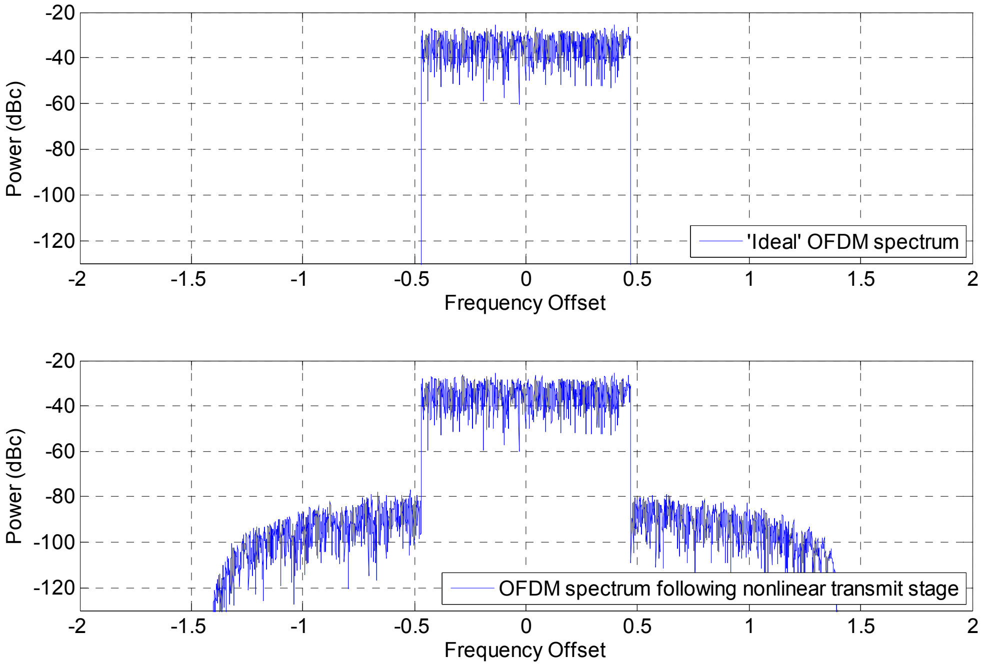

Figure 6 The effects of transmitter nonlinearity when applied to a linear modulation scheme such as OFDM.

Figure 6 shows why good transmitter linearity is essential when using linear modulation schemes such as OFDM. We have also explained why simply using overrated linear PAs backed off to ensure good linear characteristics is typically unacceptable due to very poor efficiency. There are, however, several digital techniques that can be used to 'linearise' PAs, which allow them to be operated well beyond levels that would otherwise be acceptable.

These techniques can be generally be grouped into two categories. The first includes techniques that attempt to compensate for nonlinearities in the PA. These typically use concepts such as pre-distortion or feed-forward correction (or a combination thereof). The second includes techniques that use novel methods of driving inherently nonlinear amplifiers in such a way as to generate the desired waveforms at the output. One example of this kind of technique is polar modulation.

Pre-distortion works by modifying the signal entering the PA such that, when combined with the nonlinear characteristics of the PA, unwanted nonlinear products at the output signal are heavily attenuated. Performance is increased in adaptive systems in which the model used to control the pre-distortion is continually updated by monitoring the output of the PA, eg, through the use of a directional coupler. The performance of pre-distortion systems is heavily dependent on the accuracy of the PA model and the ability of this model to predict how the PA will respond to any given input. However, as an example, Kim and Konstantinou [2] have demonstrated 11 to 13 dB ACLR improvements when using predistortion techniques to pre-distort UMTS carriers. As more advanced models and techniques are developed, even greater improvements may be realised.

Feed-forward correction uses a high-quality, lower powered ‘error’ amplifier in parallel with the main PA to add a suitable correction signal to the output of the main PA and cancel out any nonlinear effects. As an example, this technique may be used to improve the linearity of a Class-C amplifier by between 20 and 30 dB [3].

Polar modulation splits the wanted signal into phase and amplitude components. The phase information is used to drive a voltage-controlled oscillator (VCO) which in turn drives a very efficient, nonlinear amplifier. The output of this amplifier is then modulated by using the amplitude information to control the envelope, e.g. by adjusting the biasing applied to the output stage. As with the pre-distortion technique, performance can be improved by using feedback from the output to ‘close the loop’. Polar modulation has been successfully demonstrated for narrowband systems such as EDGE, which uses an 8-PSK modulation scheme in a 200 kHz channel, and commercial solutions exist, e.g. RF Micro Devices’ POLARIS™ 2 TOTAL RADIO™ solution [4]. However, an issue with this technique is that the bandwidth of the control signals and in particular the phase signal tends to be very great, eg, consider the phase change required when crossing zero. This issue may mean that techniques such as polar modulation are less well suited to use in wideband systems such as UMTS and WiMAX.

The complexity of the linearization techniques available varies greatly, with concomitant variations in performance. In particular, some of the simpler techniques/implementations that may be applied to great effect in narrowband systems are less effective when used with wideband systems because wideband amplifiers tend to exhibit temporal and frequency-selective nonlinearities. PA linearization is a complex topic and a more in-depth discussion is outside the scope of this report. However, further information is widely available; one suggested source of information is Kenington [3].

- *Receiver selectivity*

Moving to consider the performance of the receiver, the equivalent of OOBE is receiver selectivity. Ideally, the receive filter will pass the wanted band exclusively. However, as with the transmit filter, this is not generally possible and suppression of out-of-band signals will be finite. The selectivity of a receiver refers to its ability to suppress out-of-band signals.

An example is shown in Figure 7. In Figure 7 (top), the output from an 'ideal' transmitter is received in the adjacent channel. Ideally the receive filter would reject virtually all of this signal. However, a practical filter implementation cannot match the adjacent channel rejection of the ideal filter so some of the power from the adjacent channel interferer reaches the demodulator, as shown in Figure 7 (bottom). This power will reduce the SIR for wanted signals and hence reduce the sensitivity of the receiver.

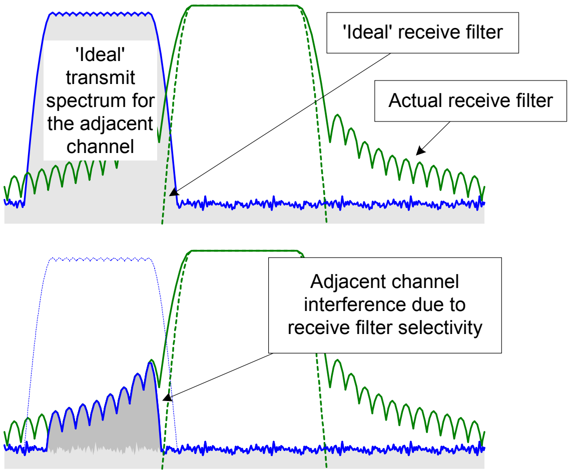

Figure 7 Interference through non-ideal receiver selectivity.

Generally receiver selectivity can be improved by increasing the complexity of the baseband channel filters and, to a lesser degree, using higher-order analogue filters at the RF input. However, both of these options typically involve greater cost and, in the case of the implementation of the baseband filters, potentially higher power consumption. Nevertheless, operators operating equipment in bands adjacent to third-party equipment, especially when different technologies are involved, may require greater selectivity and may consider the associated costs acceptable.

A typical measure of receiver selectivity is adjacent channel selectivity (ACS), which is essentially the attenuation offered to an adjacent channel signal by the receiver.

- *Receiver blocking performance*

Receiver selectivity refers to a receiver's ability to reject adjacent channel signals. As stated above, power from adjacent channel signals reaching the demodulator will reduce SIR and hence sensitivity. Sensitivity is typically limited by the performance of the channel filter, which is generally implemented at baseband. Although the range of frequencies allowed to enter the RF front end is normally restricted by the use of an analogue RF bandpass filter, this filter will typically pass a relatively wide range of frequencies. Normally this is satisfactory as the RF front end will handle any adjacent channel signals with ease. However, in extreme circumstances, e.g. when collocated with transmitter equipment operating within the bandwidth of the RF filter, strong adjacent channel signals can 'block' the input to the receiver from receiving the wanted signal. Blocking can occur if the interfering signal forces the receiver to reduce its gain; reducing gain will degrade the sensitivity. If the gain is not reduced and the RF front end enters compression, the resulting intermodulation products can manifest themselves as significant in-band interference power and the wanted signal will become heavily distorted.

Thus, blocking performance is generally limited by the dynamic range of the RF analogue front end. Blocking performance can therefore be improved by two means. First effort can be expended to increase the dynamic range of the receiver by improving the 1-dB compression point. However this can only be done to a limited extent and typically increases power consumption of the amplification stages. The other approach is to improve the RF filtering, i.e. prevent the out-of-band signals entering the receiver in the first place. Drawbacks of this approach is the increased size, complexity and cost of the filters and, by virtue of the fact that the filter is optimised for the wanted frequency, the potential loss of flexibility in terms of reconfiguring the receiver for operation on different frequencies, e.g. in response to frequency plan updates.

- *Net filter discrimination*

We have discussed transmitter performance in terms of OOBE and receiver performance in terms of receiver selectivity. In practice, of course, the observed performance will be a combination of the two, i.e. SIR will be reduced by OOBE from the transmitter falling within the passband of the receive filter and also by power in the adjacent channel 'leaking' through the stopband of the receiver filter. A measure of this combined performance is net filter discrimination (NFD). Essentially this is an estimate of the power entering the demodulator (i.e. after the receive filter) of a typical signal in an adjacent channel normalised to the power of an equivalent co-channel, i.e. wanted, signal. The general process is shown in Figure 8.

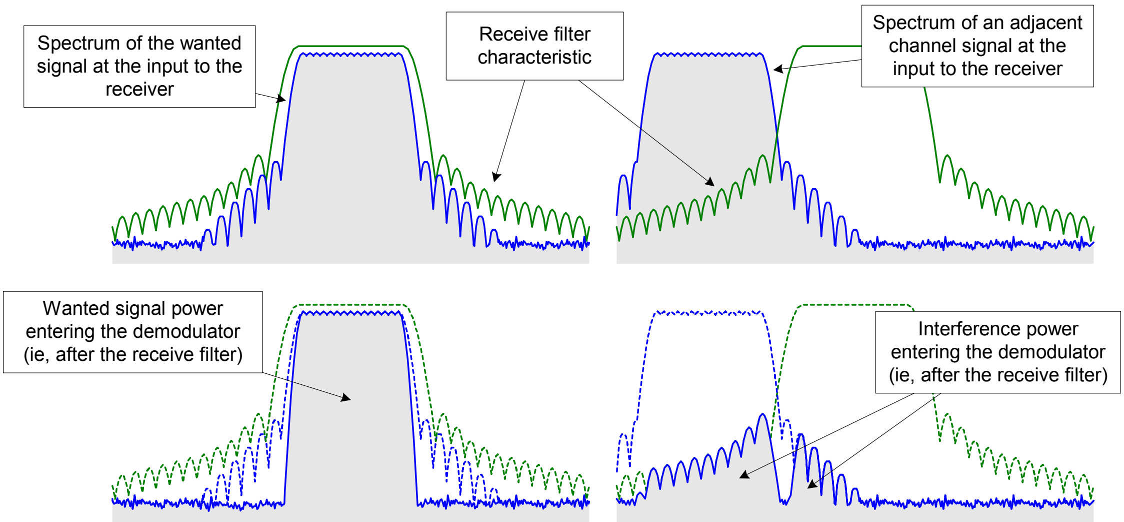

Figure 8 Net filter discrimination is the ratio of power in the wanted signal (top left) reaching the demodulator (bottom left) to that of an equivalent signal in the adjacent channel (top right) reaching the demodulator (bottom right).

Worst-case scenario NFD values can be estimated using the transmission mask to represent the spectrum of the interfering signal. However, more realistic and less pessimistic figures can be obtained by characterising 'typical' transmitter equipment.

- *Antenna discrimination (BS-to-BS interference)*

When collocating BS equipment, careful positioning of the antennas can make a great difference to the levels of isolation that can be achieved between the different systems. All antennas have a non-isotropic radiation pattern that can be characterised for any given frequency. More specifically, most antennas have nulls in their radiation pattern, i.e. directions in which negligible gain is observed with respect to the maximum forward gain. If the multiple antennas systems are simply mounted next to each other with no regard to the characteristics of each antenna, significant coupling between the antennas may occur. However, by carefully positioning the different antennas such that the nulls are aligned significant levels of isolation between the antennas can often be achieved.

The potential to increase inter-system isolation through antenna discrimination will typically be greater when considering point-to-point data links that use highly directional antennas. In this scenario, the antennas will typically have relatively high forward gain and narrow beamwidth and, whilst sidelobes will exist, the power in the sidelobes will be much reduced compared to the main beam (e.g. 30 dB attenuation [1]) and there will generally be numerous nulls that can be exploited. Note that using a more directional antenna with a narrower beamwidth may also help reduce coupling caused by RF energy reflecting off of nearby buildings and other objects. Although directional antennas may be preferable, even sector antennas with 120° horizontal beamwidths typically have relatively narrow vertical beamwidths. Therefore vertical separation of antennas can often be used to good effect to help achieve good isolation between systems, even with cellular sector antennas.

As a final note, when considering collocated BS systems, simply increasing the separation between the respective antenna systems can have a considerable effect on inter-system isolation. For example, 3 m (10') separation corresponds to a free-space loss of 50 dB at 2.5 GHz.

- *Antenna discrimination (BS-to-SS/SS-to-BS interference)*

  Antenna discrimination is also applicable to mitigating BS-to-SS and SS-to-BS interference.

  When considering fixed point-to-point wireless links the use of highly directional antennas should be considered. The benefits are twofold. Firstly, as directivity is increased, i.e. as beamwidth is reduced, the gain of an antenna generally increases. Thus, the same effective isotropic radiated power (EIRP) can be achieved with considerably reduced transmit power, which lowers power consumption and either enables a PA with lower power rating to be used (which reduces cost) or allows the PA to be backed off further which will improve linearity and help reduce OOBE.

For example, if a 7 dBi antenna is replaced by a 17 dBi antenna the output of the PA can be reduced by 10 dB to maintain a constant EIRP. Reducing the output of the PA by 10 dB will reduce out-of-band third-order IMPs generated by the PA by 30 dB. Thus, radiated OOBE due to nonlinear effects in the PA would undergo a 20 dB net reduction in the direction of the main beam. Even greater reductions would be observed outside of the main beam of the antenna.

The second benefit of using directional antennas is that RF power is directed to/received from the intended transceiver only, which helps minimise interference (both co-channel and adjacent channel) caused to and received from other users. Thus SIR can be maximised.

Note that there are numerous advantages to maximising SIR. This is especially true when considering the latest advanced radio technologies, which are able to adapt the modulation method and channel coding to take advantage of improved SIR. Thus, by improving SIR, higher-order modulation and/or lower-rate channel coding schemes can be selected, which permits higher data rates to be sustained or, through freeing up radio resources, allows more users to be supported. Even in radio technologies that do not support adaptive modulation and/or channel coding, increasing SIR generally will enable greater frequency reuse, which implies better spectral efficiency.

For fixed point-to-multipoint or mobile applications the use of directional antennas is less practical. For the former the BS needs to direct power in multiple directions simultaneously and to construct an antenna to achieve this is impractical. To use a separate antenna for each user (assuming that there are more than one or two users) is similarly impractical. (Note that generally the SS will still benefit from a directional antenna, however.) For the latter the users are, by definition, moving so a fixed beam pattern is of little use. A solution to both scenarios is the use of adaptive, smart antennas. These come in various guises but the more advanced use beamforming techniques to a) focus gain, i.e. power, along the bearings of interest and b) direct nulls at known sources/recipients of interference. Thus, smart antennas have the potential to bring some of the benefits offered by fixed, directional antenna to applications involving multiple and/or moving targets and help maximise SIR.

- *Antenna polarisation*

Taking the concept of antenna discrimination a stage further, we note that the electromagnetic output from an antenna can often be polarised in a number of different ways; the polarisation of some antennas is a feature of the design; other antennas, e.g. multi-fed patch antennas can actually produce different polarisations depending on how they are fed. For maximum coupling between antennas, both transmit and receive antenna should have matched polarisations. Conversely, if the polarisation is different, i.e. 'cross polarised' then some loss is experienced. This feature may be used to improve antenna isolation where multiple antennas are collocated. Thus, one approach might be to configure FDD systems to use one form of polarisation and TDD systems another. If cross polarisation is used, 10 to 15 dB of isolation may be achieved [1].

Note that although linear polarisation may be used effectively in line-of-sight (LOS) point-to-point radio links, less discriminative antennas are often required for use in cellular networks that a) need to communicate with arbitrarily orientated SSs and b) operate in multi-path environments that may have a randomising effect on the polarisation of the received signal. Nevertheless, whilst antenna polarisation may not be beneficial when considering BS-to-SS and SS-to-BS communications, there may be gains when considering BS-to-BS interference in TDD-TDD and FDD-TDD coexistence scenarios.

- *Active interference cancellation techniques*

  The preceding factors are essentially all hardware related (ignoring the fact that channel filtering is typically performed in the digital domain at baseband). There may also be some scope for digital signal processing (DSP) techniques to be used to improve operation in the presence of strong interfering signals. In simple terms, if the effect of the interfering signal can be modelled then, by subtracting the interfering signal from the received signal the SIR can be improved for the wanted signal.

  Such approaches are typically computationally intensive and may also require highly accurate characterisation of the signal path, accurate estimation of the interfering signal, and large dynamic range in the analogue signal path. Nevertheless, this is an area that, if used with other mitigation techniques may be used to improve performance in the high interference environments.

2.5.2 Deployment Factors

In addition to the technology factors listed above, the following deployment factors may also affect performance in a coexistence scenario:

- *BS location*

  The relative location of the BS equipment in coexistence scenarios can have a significant impact on the ability for the various systems to coexist. Considering BS-to-SS interference, then there may be considerable advantages to collocating BS equipment as this ensures consistent SIR levels across the coverage region, as shown in the example of Figure 3. In harmonised FDD-FDD and synchronised TDD-TDD coexistence scenarios BS-to-BS interference is not typically a major issue because the case in which a receiver has to operate on a frequency adjacent to an operating transmitter is avoided. However in FDD-TDD and unsynchronised TDD-TDD scenarios this is not the case. Here collocating BS equipment may lead to crippling inter-system interference, with the transmitter of one system blocking the receiver of another.

Therefore, when considering FDD-TDD and unsynchronised TDD-TDD systems a compromise needs to be found that achieves an acceptable trade off between BS-to-SS and BS-to-BS interference.

If collocation is a requirement, various mitigation steps may be taken. One option is to improve the roll-off and rejection offered by the RF filters. However the gains that may be achieved through this approach will diminish as the separation between the frequencies of operation is reduced. Other approaches include using antenna discrimination and careful siting of the antennas to maximise inter-system isolation and, if possible, use the mounting structure to shield one antenna from another.

If the BS equipment is not to be collocated then suitable man-made and/or geographical features may be exploited to shield one BS from another. The key point here is that the BS should not be arranged so that they 'fire' at one another or are positioned as in Figure 3 (top) which may lead to significant interference problems resulting from the near/far effect.

- *SS location*

When considering fixed wireless links the SS may be treated in a similar manner to BSs as it is a stationary transceiver, often using a fixed antenna with moderate directivity. Therefore, care should be taken to maximise isolation with other nearby systems by carefully choosing and siting the antenna and, if necessary, augmenting the RF filtering. In the case of mobile SSs, then, by definition it is impossible to control their locations relative to one another. Furthermore, a low gain, omnidirectional antenna is typically required for ease of use, which means that techniques such as antenna discrimination are impractical.

- *Use of site features for shielding*

As discussed above, site 'features' be they man-made or natural may be used to great effect to improve isolation between one system and another by using them to shield one antenna from another. The level of isolation that may be achieved will vary from site to site and will be dependent on the characteristics of the 'shielding materials' and reflections from nearby objects. The use of site features for shielding is applicable to both BSs and 'fixed' SSs.

- *Frequency planning*

  Where techniques such as the exploitation of site features and antenna discrimination are not available or are unable to provide sufficient isolation then the use of high performance RF filters may be necessary. Practical filters can only achieve finite roll-off rates. Moreover, if the passband of the filter is too heavily constrained then phase distortion, which causes delay variations, may have a significant impact on signal integrity. Therefore the analogue filter may impose practical limits on the separation required between active frequency bands. This in turn means that careful assignment of the available channels to the BS sites may be required to not only keep co-channel interference levels to acceptable levels but also ensure that there is always sufficient frequency separation between carriers used by different systems at each site with collocated BSs. Note that the ability of operators to achieve this may depend on the relevant operators agreeing to cooperate and to work out procedures to share the data needed to enable the coordination of frequency assignment plans.

- *Inter-operator cooperation and coordination*

  If multiple operators are to be allowed to operate different radio systems in adjacent spectrum in the same geographic location then cooperation and coordination between operators is likely to be essential. If operators choose to operate behind closed doors and deploy and operate their equipment independently problems may be inevitable. In particular, new equipment deployed by one operator may adversely affect the service already established by another.

In the TDD-TDD scenario encouraging inter-operator coordination is probably not too difficult because interference issues, if they occur, are likely to be bilateral, i.e. if Network A suffers interference from Network B then in all likelihood Network B will also suffer interference from Network A. The FDD-FDD scenario is similar although, as discussed previously, there is less scope for problems in an FDD-FDD scenario.

Problems are most likely to occur in the FDD-TDD scenario in which the most severe forms of interference are unilateral, i.e. BS-to-BS interference affects the FDD system when a TDD system is deployed adjacent to the FDD UL and affects the TDD system if deployed next to the FDD DL. Therefore some additional incentive and/or making inter-operator cooperation a condition of spectrum access may be necessary.

Inter-operator cooperation and coordination may achieve the following goals:

- *TDD synchronisation* – A massive reduction in the potential for inter-system interference in a TDD-TDD coexistence scenario can be achieved by synchronising the transmissions from the relevant systems. Thus the scenario in which one BS transmits whilst in the close proximity of a BS trying to receive is avoided. As mentioned in Section 2.4.3, TDD synchronisation is only practical when all systems implement a common, fixed timing structure.

  There may also be situations in which there is some gain to be had by synchronising TDD systems to HFDD systems, e.g. if HFDD systems were deployed to utilise 'guard' channels inserted between adjacent TDD and FDD systems.

- *Frequency plan coordination* – The characteristics of practical RF filters mean that the closer nearby systems are in frequency to one another, the harder it is to achieve the necessary inter-system isolation. Operators with multi-channel licenses could carefully engineer their frequency assignments to try and mitigate adjacent and co-channel interference. When considering ‘band-edge’ channels, neighbouring operators may be able to optimise their networks by sharing and coordinating their frequency plans. Whilst the release of network configuration data is unlikely to be well received by operators, doing so may allow each to make more efficient use of their allocated spectrum. If cooperation and mutual consent cannot be reached, then guard channels will be mandatory with a consequent loss in spectral efficiency.

- *BS and antenna location coordination* – In a similar way that consensual frequency planning may facilitate greater overall spectrum utilisation, cooperation and coordination when planning the siting of BS and antenna equipment may also be beneficial to the operators concerned.

3 Studies to Date

As part of this work, a review of some of the many studies into the coexistence of FDD and TDD systems that have been completed to date was performed. The abstracts from the documents found as a result of a literature search are reproduced in Appendix A and the main findings of the review are presented in the remainder of this section. Note that this review was restricted to literature published in the public domain.

The studies identified that investigate the co-existence of TDD and FDD systems primarily involve the scenario in which different systems operate in the same area but on adjacent channels. Most of these studies are simulation based and present their results in terms of the capacity loss or outage probability as a means of measuring and analysing the impact of co-existing systems. Note that the majority of these studies (and hence their conclusions) are specifically concerned with the performance of UMTS systems. Given that systems using CDMA technology are inherently interference limited and, as a result, include mechanisms such as power control to dynamically adjust to ‘ambient’ interference levels, the findings of these studies may not be directly applicable to systems that are typically noise limited, i.e.

are not designed to simultaneously share spectrum with other users eg, some OFDM systems.

Four interference paths are identified and considered; interference experienced from base station to base station (i.e. BS-to-BS), interference from mobile station to mobile station (i.e. SS-to-SS), interference from mobile station to base station (i.e. SS-to-BS) and the interference from base station to mobile station (i.e. BS-to-SS). (These concur with the interference paths that were identified in Section 2.4.) In general, BS-to-BS interference is believed to be the main and most damaging interference path [5][6][7]. SS-to-SS interaction is also identified as a potentially severe source of interference, specifically if the two SSs are geographically or spectrally too close to each other [7][8][9][20]. One study identifies SS-to-SS interference as the main interference path [10]. This result is due to the ACS and ACLR values assumed for the SS and BS; the adjacent channel interference ratio (ACIR), effectively a measure of net filter discrimination, for the BS-to-BS path was calculated to be 12 dB greater than that for the SS-to-SS path.

According to [5], system performance is dependent on the frequency offset between the interfering BSs, ACIR and the BS and SS transmit power. Moreover, it finds that if the performance of one system is affected the performance of the other system is affected as well, which leads to the conclusion that system performance depends on the loading of *both* FDD and TDD systems. Therefore, in order to optimise the performance of both systems, some cooperation and compromise is required between the system operators.

Earlier work addressing SS-to-SS and SS-to-BS interference [8][11][12][13][14][15] suggests that with a 5 MHz carrier spacing, TDD/FDD co-existence is feasible based on the ACLR/ACS requirement thereof and that no additional guard bands are required. Reference [16] concurs that the C/I requirement can be met with high probability in most realistic scenarios. A number of studies conclude that there is adequate power available in the UMTS TDD system to handle interference from UMTS FDD, so there is negligible impact on the TDD system's capacity due to a FDD system in the adjacent channel, however, minor capacity loss is experienced by the FDD UL if the TDD BS is located too close to the FDD BS [10][16][17][18]. Reference [9] concludes that co-existence can be supported provided that ACIR is better than 70 dB and BS separation is greater than 200 to 300 m. Moreover, since there is no duplex filter available to isolate the transmit and receive frequencies in TDD systems, the TDD transceiver requires a higher ACIR than that in the FDD system.

More recent work on sharing using OFDMA modulation was done in CEPT SE19 which performed coexistence studies in [19] and [20], those studies were between BWA systems operating in the 3.5 GHz band. The studies analyse the interference situation which occurs between WiMAX FDD and TDD or between unsynchronized TDD systems in terms of the amount of guard band.

It should be noted that the 3GPP UMTS specification makes no guarantee that the co-siting of TDD and FDD systems in the core bands is feasible [6]. Moreover, whilst the ACLR and adjacent channel protection (ACP) specifications of the TDD BS are adequate to combat interference when co-siting, the ACS and blocking performance of the FDD BS is not, so additional filtering is required, which is reported to be technically and economically viable.

A more comprehensive study has been addressed in [7], covering a range of scenarios to investigate the separation distance required for TDD/FDD coexistence, the ACIR required for 3.84 Mchip/s TDD/FDD coexistence and the separation distance required for TD-SCDMA/FDD coexistence. It concludes that a potential problem is when BS transmitters are geographically and spectrally close to sensitive SS receivers, regardless of the duplex method. Large separation distances and additional isolation are required in several scenarios to combat interference (while some other scenarios do not have such requirements). Moreover, it finds that the separation distance can be traded-off against coverage and increased SS transmitter power in the victim system. Finally, [7] concludes that the collocation of BSs will become prevalent in future systems. However, when considering existing WCDMA specifications, even 5 and 10 MHz guard bands are not sufficient to overcome the potential interference issues.

Solutions to combat the BS-to-BS interference have been proposed in [1][7][21][22]. These include additional RF filtering, careful site placement, antenna separation, antenna polarization, adaptive (i.e. smart) antenna arrays, power control and radio link adaptation. The application of smart antennas in TD-SCDMA systems is investigated in [23] and finds that they can be used not only to suppress the interference from TDD systems to FDD systems, but also protects the TDD system from FDD interference. The impact of adjacent channel interference on capacity and the ability to compensate this by dynamically increasing BS power is been studied in [24]. Finally, the use of TDD frequency reuse to minimize the interference from TDD systems to FDD systems is addressed in [25].

4 Regulatory Considerations

Regulators have an obligation to take all reasonable steps to ensure that the equipment operated by one spectrum user does not cause unacceptable interference to equipment operated by another. This is especially true when licences are awarded through beauty contests and auction processes in which considerable sums of money can be exchanged for the right to operate in a particular part of the RF spectrum. When such substantial financial commitments are made on the part of the licence winners it is reasonable that they expect some form of guarantee from the regulator regarding the interference levels that may be experienced. Some compromise is needed, however. Political drivers for competition and liberalisation in service provision often provide pressure for a number of licences to be awarded within any given area (regional or national); where these licence areas overlap, competing operators can find themselves operating in close proximity to each other.

Traditionally, where spectrum usage has be governed rigidly and the technology and service types have been predefined, the interaction between adjacent systems has been relatively predictable, which has enabled the regulators to make informed decisions regarding guard bands and maximum radiated power levels. However, with the advent of spectrum liberalisation, the relationships are far less predictable and the permutations far more numerous. This means that a new approach may need to be adopted when planning future spectrum releases and for more generic and more flexible usage polices to be adopted in preference to rigid, inflexible channel allocations. Moreover, there may be arguments for a means by which the 'default' rules can be relaxed when operators operating in adjacent channels can agree to cooperate and find mutually acceptable deployment policies. Whilst this complicates matters, such an approach may enable otherwise 'unusable' spectrum to be utilised, which would be a win-win situation for regulators and operators alike.

A significant contributor to interference between coexisting wireless systems are the emissions from devices operating outside the band of frequencies designated for operation, i.e. OOBE. However, even 'in band' power will affect coexistence for the reasons discussed previously, e.g. receiver selectivity, receiver blocking, etc. Furthermore, we note that OOBE is inherently linked to transmit power, typically with both first- and third-order components, e.g. filter performance and PA linearity, respectively. In other words, limiting transmit power will have a limiting effect on OOBE also.

The traditional approach to dealing with these problems has been to define maximum transmitter powers and to identify guard frequency bands between operator blocks, which relies on frequency discrimination to provide some of the isolation required between nearby systems. However in certain scenarios a rigid fixed guard band can limit flexibility and prohibit schemes that might make use of otherwise unusable spectrum. Furthermore, these methods tend to be technology specific. Therefore alternative, less technology specific methods are required.

4.1 Transmitter Power

For any given radio technology, maximum transmit powers are normally given for the various classes of equipment defined. These limits, which are necessary to facilitate spectrum reuse and to limit adjacent channel interference levels at the receiver, take into account factors such as signal bandwidth, modulation and multiple access methods and are inherently technology specific. When considering technology neutral bands, technology specific limits are not appropriate. Therefore, a clear, unambiguous method of limiting transmitter power is required.

An example of how maximum transmitter power may be defined in a technology neutral manner is given in the Code of Federal Regulations (CFR) 47CFR27.50(h) [26], developed by the US Federal Communications Commission (FCC). Here, the EIRP for BSs operating either broadband radio services (BRS) or educational broadband services (EBS) in the 2150 to 2162 and 2496 to 2690 MHz bands must not exceed

$$\mathrm{EIRP} = 33 + 10 \cdot \log_{10} (X / Y) + 10 \cdot \log_{10} (360° / \mathit{beamwidth}) \text{ dBW}, \qquad (1)$$

where X represents the channel width, in MHz and Y is either 6.0 MHz if in the middle band segment or 5.5 MHz if in the upper or lower band segments. *beamwidth* represents the horizontal 3 dB beamwidth, in degrees, of the transmitting antenna. Note that for omnidirectional antennas, the *beamwidth* is 360°, i.e. the last term is equal to zero.

The inclusion of X in Equation 1 means that this equation effectively defines a maximum power spectral density, with an adjustment for antenna beamwidth. This is underlined by the ‘small print’ of the ruling that states that this maximum EIRP assumes a uniform power spectral density. If power spectral density is not uniform, the ruling states that the power in any 100 kHz bandwidth must not exceed that of a uniform transmission with an equivalent EIRP. Thus, if Equation 1 returned a maximum EIRP of 33 dBW (2 kW) in 6 MHz, the maximum power allowed in any 100 kHz within the 6 MHz would be 15 dBW (33.3 W). This corresponds to a power spectral density of 25 dBW/MHz.

For mobile stations EIRP is limited to 3 dBW (2 W) irrespective of signal bandwidth. For other SSs, transmit power, i.e. exclusive of antenna gain, is limited to 3 dBW (2 W). This effectively allows directional antennas to be used in SS installations to achieve EIRPs greater than 2 W.

4.2 Out-of-Band Emissions

Specifying maximum EIRP in a technology neutral manner is not too complex a task. Specifying OOBE limits, however, is potentially much more difficult. Traditionally OOBE limits can be calculated knowing not only the characteristics of the transmitted signal but also those of the receiver, i.e. what interference levels can be tolerated before signal degradation becomes unacceptable. As stated previously, a traditional approach has been to pre-define suitable guard bands. In a technology neutral environment, however, the characteristics of the radio technology are not known. Moreover, if the permitted systems operate different channel bandwidths, the concept of fixed guard bands becomes impractical.

Rather than defining the guard bands explicitly, a means is required by which suitable guard bands, the width of which is appropriate for the technology deployed, can be derived. One approach is to define OOBE constraints either in the form of a block edge mask or a general signal mask. Thus, whereas guard bands rigidly prohibit access to selected frequency bands, a mask-based approach takes the performance of the radio equipment into consideration and/or may allow the use of equipment at lower transmit powers, i.e. shorter ranges. Together, better spectrum utilisation may be realised.

The use of a block edge mask is recommended by the Electronic Communication Committee (ECC), part of the European Conference of Postal and Telecommunications Administrations (CEPT), in Recommendation (04)05 [27]. This mask, reproduced in Figure 9, defines the power that may be radiated into spectrum adjacent to a licencee's assigned 'block' in absolute terms. Note that, however, the required roll-off is proportional to the width of the assigned block. Thus the mask is completely technology neutral; it makes no assumption regarding duplex methodology or even channel bandwidth.

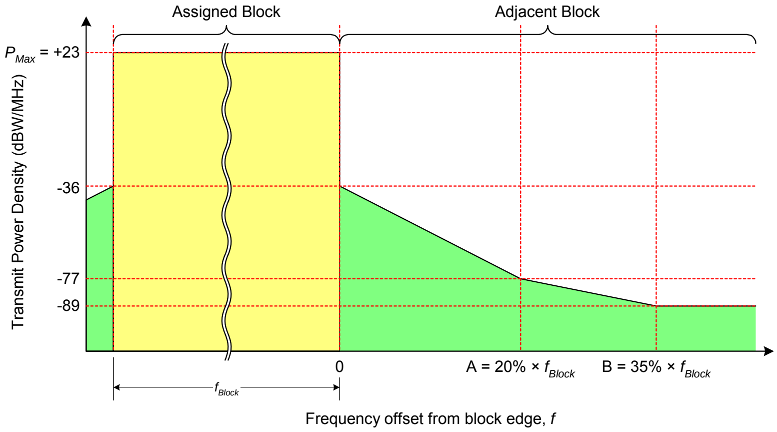

Figure 9 BS block edge spectral density mask defined in ECC Recommendation (04)05.

This mask clearly defines what power may be emitted outside the block of spectrum assigned to a particular operator. Armed with knowledge of the characteristics of its transmitter equipment, an operator may conform to the mask in a number of different ways. These include:

- Implement a self-imposed guard band within the assigned block so that OOBE remain below the mask.
- Configure transmitters operating close to the block edge to transmit at a lower power, thereby reducing OOBE (and range).
- Reduce OOBE by specifying equipment with improved RF performance, eg, improved PA linearity, for transmitters operating close to the block edge.
- Fit additional RF filtering to transmitters operating close to the block edge to suppress OOBE to acceptable levels.

Finally, it should be noted that Recommendation (04)05 further states that if operators of adjacent frequency blocks agree to cooperate then the levels shown in Figure 9 may be exceeded by mutual consent. In practice this means that operators may alleviate potential interference issues near the block boundary by coordinating their frequency plans.

The ECC is not the only organisation to propose the use of block edge masks, the FCC has also considered the use of block edge mask requirements to control the potential emissions from different wireless systems and technologies operating on adjacent channels [28]. Recognising the need to maximise spectral efficiency whilst protecting operators from interference, the FCC has adopted a so-called ‘dual mask’ approach for BRS and EBS equipment, which is shown in Figure 10.

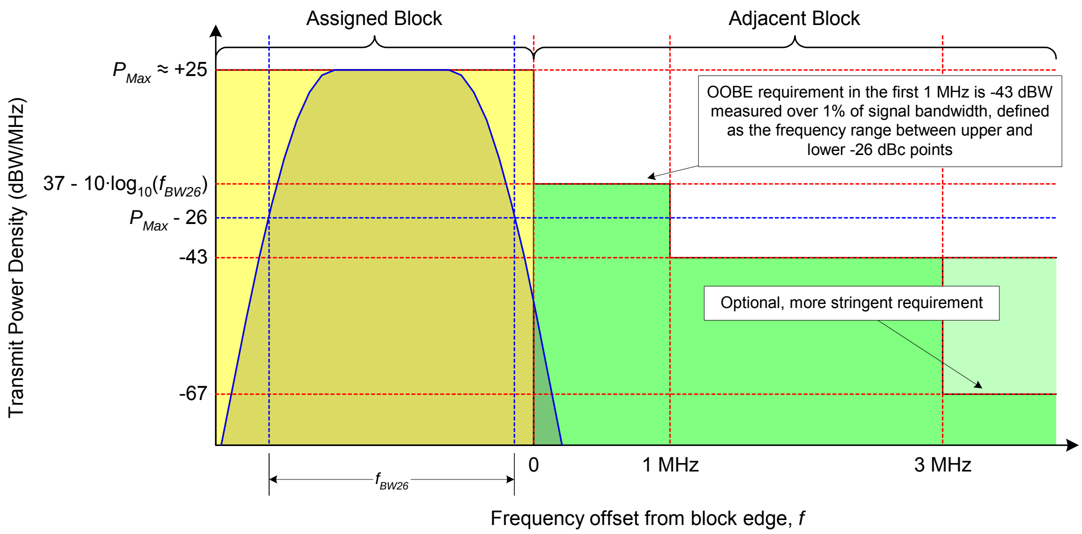

Figure 10 Interpretation of the FCC dual mask specification for BRS and EBS equipment.

The ‘default’ requirement is that OOBE measured from the band edge must be attenuated by no less than 43 + $10 \cdot \log_{10}(P)$ dB at the band edge, where P is the transmitter power in W. This equates to a level of −43 dBW (−13 dBm). In the first 1 MHz adjacent to the assigned block, a measurement bandwidth equal to 1% of the emission bandwidth[2] is specified. Thus, for example, if the transmitted signal has a 5 MHz emission bandwidth, the equivalent power spectral density is −30 dBW/MHz (0 dBm/MHz). Beyond the first 1 MHz, a 1 MHz measurement bandwidth should be used, so the OOBE requirement translates into a maximum power spectral density of

[2] The emission bandwidth is defined as “the width of the signal between two points, one below the carrier center frequency and one above the carrier center frequency, outside of which all emissions are attenuated at least 26 dB below the transmitter power”.

−43 dBW/MHz (−13 dBm/MHz). This is intended to be a relatively relaxed requirement, designed to promote high spectrum utilisation.

In certain circumstances, the −43 dBW limit may not be sufficient and unacceptable interference may be caused users operating in the adjacent block. In the first instance, operators will be encouraged to reach a mutually acceptable solution, eg, through the coordination of frequency plans, upgrading of transmitter equipment, etc. However, if such a solution cannot be found then, on submission of a documented interference complaint, both parties will be required to instead adhere to stricter OOBE attenuation requirements.

Assuming that the affected equipment are separated by 1.5 km or more, the optional OOBE requirement is that OOBE integrated over a 1 MHz measurement bandwidth are attenuated by no less than $67 + 10 \cdot \log_{10}(P)$ dB when measured 3 MHz from the channel edge. This corresponds to a power spectral density of −67 dBW/MHz (−37 dBm/MHz), i.e. an additional 24 dB attenuation. If site separation is less than 1.5 km then even greater attenuation is required. These stricter levels are designed to limit any desensitisation of uncoordinated equipment operating in the adjacent channel to 1 dB[3] [29]; a 1 dB desensitisation is considered to be an acceptable compromise between enabling high spectral utilisation and protecting operators in adjacent bands. In practice, the 1 dB desensitisation limit is achieved by ensuring that the interference power spectral density at the input to the receiver is 6 dB below the noise floor of the receiver.

In essence, this dual mask approach is designed to encourage operators to cooperate in return for a relaxed OOBE requirement. However, for cases where this fails, there is a documented ‘fall back’ plan. As with the ECC recommendation, the FCC has also included provision to allow operators to replace the FCC OOBE limits

[3] Note that the FCC does not specify an antenna gain or a noise figure, both of which are required to determine the actual noise rise. Higher gains or lower noise figures will case the desensitisation to be increased.

with less stringent limits that are mutually acceptable to the parties affected. Thus there are in fact *three* levels of OOBE control!

The concept of a block edge mask should permit the regulator to take a back seat, stepping in only to resolve disputes. A possible alternative to the use of block edge masks would be to extend the concept of 'guard band managers', currently employed in the US to control access to selected bands in the range 746 to 794 MHz [30]. Here, from the point of view of the regulator, the guard band manager is the licensee. The guard band manager then effectively subleases its spectrum to the network operators. Thus, it is the guard band manager who is responsible for the coordination of the spectrum users (both in terms of frequency and space), the enforcer of guard bands and the resolver of spectral disputes.

4.3 Smart Antennas

In any cellular system, one of the challenges for the operator is to provide the subscriber with consistent performance across the coverage area. Typically this requires the use of a multiple BSs, with a frequency reuse ranging from one, i.e. a single-frequency network, eg, WCDMA, to, say, seven. One technique that has traditionally been used by network planners to optimise coverage and/or capacity is cell sectorisation. Sectorisation effectively involves the process of splitting cells with omnidirectional coverage into a number (typically three) of smaller cells or 'sectors'. Sectorisation is essentially a cost effective method of 'cell splitting', a proven method of improving network performance. However, sectorisation can only deliver finite gains and these gains diminish as more sectors are added to a site [31].

Sector antennas generally have relatively rigid characteristics; perhaps with the exception of optional features such as electronic down-tilt, the beam pattern is fixed. Smart antenna systems introduce the concept of beam agility and represent an evolutionary step in BS implementation. With this capability, smart antennas can 'track' users and, by dynamically adapting the composite beam pattern, realise significant SIR gains that, in turn, can be used to improve coverage and/or capacity and reduce interference caused to and received from other networks operating in the vicinity. WiMAX technology supports adaptive antenna systems (AAS).

In their simplest form, smart antennas may consist of a number of fixed-beam antennas. Thus, users can be tracked by switching from one antenna to another. Ultimately, however, smart antenna systems may use multi-element antenna arrays together with advanced beamforming techniques to simultaneously track both users and interferers alike. Thus, by focusing gain on cell's users whilst simultaneously steering 'nulls' at sources/potential recipients of interference SIR can be maximised.

Smart antennas would appear to have the potential to offer significant spectral efficiency and/or throughput gains, with benefits for regulators and operators alike. For example, they focus the 'wanted' signal to where it is required, which will certainly reduce adjacent channel interference due to leakage at the receive filter, i.e. poor receiver selectivity of receivers using the adjacent spectrum.

Therefore, smart antennas are a good idea and regulators should encourage their adoption. However, there are some points that smart antennas (including adaptive beamforming smart antennas) raise that the regulator should consider.

The in-band power and OOBE will vary in time as the antenna weights change to direct power to different users. Typically, beamforming is performed at baseband by applying complex weights (i.e. amplitude and phase) to the waveforms sent to and received from the various antenna elements. When the individual signals are combined (at baseband in the receive case and in the radio channel in the transmit case) beam patterns are realised. In a linear system the relationship between the element weights and corresponding beam pattern is straightforward, and one would expect the beam pattern of the OOBE to be similar to that of the inband signal. In practice, however, BS transmitters are not perfectly linear and nonlinearities in the PA, cause the amplitudes and phases of the OOBE to be different to those of the wanted signal. Phase and gain differences between filters in the elements may also have similar effects. The consequence is that for a single beam, beam shape of the OOBE will differ from that of the in-band signal. As a result, nulls in the wanted signal beam may contain OOBE power, and it may not be practical to attempt to steer the OOBE power and the inband power away from potential interference victims.

However OOBE power in other directions may be lower relative to the in-band power.

Relative to single antenna systems, smart antennas reduce in-band power transmitted in unwanted directions and have the potential to reduce OOBE.

4.4 Coexistence between Systems in Different Geographic Regions

So far in this report we have considered the coexistence of different technologies in adjacent spectrum but in the same geographic region. There is of course also an equivalent range of coexistence scenarios for co-channel operation but in *different* geographic regions. A situation in which these scenarios might exist is along international borders, for example.

When considering mitigation of co-channel interference between dissimilar systems some of the factors and techniques identified previously are no longer applicable. For example, OOBE become insignificant because the interference will be predominantly from ‘in-band’ emissions. Also filtering techniques and ACLR and ACS performance will be of little significance for similar reasons. Some of the listed techniques will still be of use, however. Directional or smart antennas, antenna polarisation and inter-operator coordination and cooperation may all be beneficial. Moreover, when considering cross-boundary interference, cooperation between regulators may also be required in order to promote operator interaction and coordination.

Fundamentally, however, interference between TDD and FDD systems operating on the same frequency can only be controlled by ensuring that there is sufficient separation between equipment so that the emissions from one system are sufficiently attenuated at the input to the other that desensitisation remains below acceptable levels. In a worst case scenario in which a both the interferer and recipient have directional antennas pointed at one another, several hundred km may be required for natural path loss mechanisms to reduce the signal power to a level where receiver desensitisation is limited to 1 dB (in the order of 200 dB attenuation may be required). Using directional antennas, etc, simply provide means of reducing the separation distances required.

5 Conclusions

Regulators worldwide are adopting the concepts of spectrum trading and spectrum liberalisation as a means of promoting and encouraging more efficient utilisation of RF spectrum. This shift from rigid and prescriptive command and control management techniques to more flexible approaches embracing the use of market mechanisms to manage spectrum access has many potential benefits for both the regulators and for the spectrum users. However, the introduction of technology neutral spectrum allocations is not without its challenges. One particular issue is the ability of systems using different duplex methodologies, namely, FDD and TDD, to coexist in adjacent frequency bands. This is an essential requirement if true spectrum liberalisation is to be realised.

Four possible interference paths have been identified. These are BS-to-BS, BS-to-SS, SS-to-BS and SS-to-SS. In this report these paths were considered in the context of the three main coexistence scenarios, namely, FDD-FDD, FDD-TDD and TDD-TDD. The FDD-FDD scenario is present in the majority of existing cellular networks and is thus well understood. The coexistence of TDD-TDD systems is also understood albeit to a slightly lesser extent. To date, however, there is little practical experience of the FDD-TDD scenario.

Discussion of the four potential interference paths in the case of the FDD-TDD coexistence scenario concluded that BS-to-SS and SS-to-BS interference is likely to be similar to that experienced in the FDD-FDD and TDD-TDD scenarios. However, it was concluded that there is a high risk of BS-to-BS interference and SS-to-SS interference. Moreover, this interference risk is unilateral. This is summarised in Table 1. Finally, considering the overall impact of inter-system interference, it was concluded that BS-to-BS interference will generally be more critical than SS-to-SS interference because SS-to-SS interference will typically only affect a small number of users and, in the case of mobile users at least, will be temporary. It was also noted that there will generally be less scope to mitigate interference issues at the SS because a) cost, weight, power and size requirements may prohibit the implementation of some of the more effective mitigation techniques and b) SSs will typically be free to roam very close to one another.

Interference Path	TDD Adjacent to FDD DL	TDD Adjacent to FDD UL
FDD BS to TDD BS	High risk	No risk
TDD BS to FDD BS	No risk	High risk
FDD SS to TDD SS	No risk	High risk
TDD SS to FDD SS	High risk	No risk

Table 1 Most severe interference paths in the FDD-TDD coexistence scenario.

Previous studies on this subject that have been completed to date generally concur with the assertion that BS-to-BS interference is the most critical interference path. Moreover, a number draw the attention to the fact that TDD systems have generally been designed to coexist with adjacent channel users and therefore already mandate adequate (or at least improved) filtering requirements. This is not necessarily the case for FDD systems where frequency discrimination afforded by the duplex spacing generally relaxes the filtering requirements greatly. Therefore, in a coexistence scenario, the TDD system may typically be more resilient to interference from the FDD system than the FDD system is to the TDD system.

Various mitigation techniques may be used to improve inter-system isolation. These include:

- *Improving transmitter ACLR performance* – Through reduction of OOBE and the use of higher-performance analogue RF filters the amount of power allowed to radiate in the adjacent channel may be reduced. OOBE may be reduced by using higher-order pulse-shaping filters at baseband and by improving PA linearity, perhaps through the use of linearization techniques.

- *Improving receiver ACS and blocking performance* – Equivalent improvements may be possible in the receiver by improving the performance of the analogue and digital filters and through improvements to the dynamic range of the analogue front end.

- *Antenna discrimination* – In fixed point-to-point applications, simple directional antennas may be used to great effect to focus power in the direction of the intended target whilst simultaneously rejecting interference power caused to and received from other users. Moreover, when collocating BS equipment, exploitation of nulls in the antenna's radiation pattern and maximising antenna separation will help maximise system isolation. In point-to-multipoint and mobile applications the use of fixed directional antennas may not be suitable. Smart (switched beam and phased array) antennas have the potential to bring some of the benefits of directional antennas to these applications..

- *Antenna polarisation* – One suggested method of improving system isolation is to use different antenna polarisation on each system. This is probably most applicable to fixed, line-of-sight links and as a mitigation technique when collocating BS equipment as polarisation information may typically be lost in a multipath environment.

- *Active interference cancellation techniques* – It is possible that future radio systems may use active interference cancellation techniques. Such techniques are likely to be computationally intensive which may limit their application.

- *BS/SS location* – Careful coordination of site placement and BS placement in particular may prove to be a very effective, low cost mitigation technique. For example, existing site features may be exploited to shield one system from another. Further coordination to minimise direct line-of-sight signal paths from one BS to another and to minimise problems from the near/far scenario will also help prevent unacceptable interference issues.

- *Inter-operator cooperation and coordination* – Key to the successful implementation of many of the above techniques and other techniques such as synchronisation of TDD and HFDD systems is the cooperation and coordination of operators. As shown in Table 1, the main interference paths in FDD/TDD coexistence scenarios are unilateral. Essentially, therefore, the situation may be created in which one operate has to compromise the deployment of their network in order to aid the deployment of a competitor's network. Such a scenario may result in reluctance on the part of the interfering network to cooperate openly. Therefore, regulators may need to be able to implement effective incentives to encourage full cooperation. This may be in the form of unilateral penalties in situations were it can be clearly demonstrated that one party is deliberately being uncooperative, eg, a development of the FCC's dual mask system.

In addition to the identification of these mitigation techniques, the following recommendations are made:

- Depending upon the deployment scenarios and the use of mitigation techniques, the size of the guard band required to successfully deploy TDD and FDD systems in adjacent spectral allocations is difficult to determine without unduly constraining one or both of the systems. Therefore it is recommended that the implementation of guard bands should be left to agreement between the operators and their regulators. Block edge masks are an effective alternative to mandatory guard bands; the operator is then free to choose how best to meet the mask requirements, the implementation of guard bands being just one such solution.

- Even without mandatory guard bands, block edge masks are likely to impose some form of restriction on the use of the spectrum at each end of an operator's assigned block. Therefore, the percentage of each operator's allocated spectrum subject to restrictions is dependent on the size of the frequency block allocations.

  For instance, if a block consists of just one or two channels, then 100% of the stations will be required to meet the block-edge mask. This may prevent optimal network deployment, which may have a negative effect on overall spectral efficiency. If instead each block consists of five channels, only 40%

of the stations will be subject to the block edge mask; stations using the central three channels can be deployed freely, potentially improving spectrum utilisation. Clearly improving spectral efficiency benefits both operators and regulators alike. Therefore it is recommended that reasonably large contiguous block sizes are considered wherever possible.

- As is the case with the findings of the ECC [27] and the FCC regulations for the BRS and EBS bands [28], operators should be given the option of replacing the default block edge masks with mutually acceptable OOBE limits. Thus, if other interference mitigation techniques, eg, the use of careful site placement and antenna orientation, are sufficient to prevent significant inter-system interference, then, through the consent of the affected operators, removal of the mask requirements may allow better spectrum efficiency to be achieved. This should not be prohibited and the provision for it in the findings of the ECC and FCC is welcomed.

- Finally we recommend that regulators assume the responsibility of encouraging or mandating that the operators of adjacent frequency blocks cooperate and coordinate their network planning. Coordinating tasks such as frequency planning and site placement are effective methods of minimising inter-system interference. If this is successful, the number of inter-operator disputes that require intervention by the regulator should be reduced.

  The bilateral gains that may be achieved by coordinating TDD networks will hopefully provide a suitable incentive for inter-operator cooperation. However, when considering TDD-FDD coexistence scenarios BS-to-BS interference tends to be unidirectional. (If all assignments, including those used by TDD systems are paired, then one half of the pair is affected by interference in one direction while the other is affected in the reverse direction and so there is an incentive to cooperate to maximise the use of spectrum.) Therefore extra incentives and/or encouragement may be required in order to gain the cooperation of the operator of the interfering network. Considering the FCC's dual mask system, maybe one option would be to only enforce the stricter OOBE requirements on the equipment of the uncooperative party (as defined the stricter mask, if invoked, is a bilateral requirement).

Finally, as stated previously, smart antennas would appear to have the potential to help mitigate interference issues in both point-to-multipoint and mobile applications.

References

1. TDD Coalition, “Tutorial on TDD Systems – Part 3: Spectrum Allocation and Coexistence Issues”, Presentation delivered to FCC Office of Engineering and Technology, 3 December 2001 [downloaded from http://www.fcc.gov/realaudio/mt120301.pdf, 8 December 2006]

2. Kim, J. and Konstantinou, K., “Digital Predistortion of Wideband Signals Based on Power Amplifier Model with Memory”, *IEE Electronics Letters*, vol 37, no 23, pp 1417–1418, 8 November 2001

3. Kenington, P., B., *High-Linearity RF Amplifier Design*, Artech House Pub, 2000

4. RF Micro Devices, “POLARIS™ 2 TOTAL RADIO™ Module”, Product Flyer, [downloaded from http://www.rfmd.com/adocs/bf/Polaris2RadioModule.pdf, 13 December 2006]

5. Lee, T., L., Faure, C., Grandblaise, D., “Impact of FDD/TDD Co-Existence on Overall UMTS System Performance”, *Veh Tech Conf 2001 (VTC 2001 Spring) IEEE VTS 53rd*, vol 4, pp 2655–2659, May 2001

6. Wilkinson, T., Howard, P., “The Practical Realities of UTRA TDD and FDD Co-Existence and their Impact on the Future Spectrum”, *Personal, Indoor Personal, Indoor and Mobile Radio Communications, 2004, PIMRC 2004, 15th IEEE International Symposium*, vol 1, pp 22–26, September 2004

7. ITU, “Coexistence between IMT-2000 Time Division Duplex and Frequency Division
Duplex Terrestrial Radio Interface Technologies around 2600 MHz
Operating in Adjacent Bands and in the same Geographical Area”, REPORT ITU-R M.2030, 2003

8. Siemens, “Simulation Results on FDD/TDD Co-Existence Including Real Receive Filter and C/I Based Power Control”, TSGR4#6(99) 419, July 1999 [downloaded from http://www.3gpp.org/ftp/tsg_ran/WG4_Radio/TSGR4_06/Docs/Pdfs/r4-99419.pdf, 15 December 2006]

9. Qingyu, M., Wenbo, W., Dacheng, Y., Daqing, W., “An Investigation of Interference between UTRA-TDD and FDD System”, *Communication Technology Proceedings, 2000, WCC - ICCT 2000 International Conference on Communication Technology*, vol 1, pp 339–346, August 2000

10. Qingyu, M., Wenbo, W., Dacheng, Y., “The Coexistence of UTRA-TDD and FDD System in the Adjacent Channel”, *Global Telecommunications Conference, 2001, GLOBECOM 2001*, vol 6, pp 3714–3718, November, 2001

11. Siemens, “TDD/FDD Co-Existence - Summary of Results”, 3GPP TSG RAN WG4#3 Tdoc 96/99, March 1999 [downloaded from http://www.3gpp.org/ftp/tsg_ran/WG4_Radio/TSGR4_03/Docs/Tpdfs/R4-99096.pdf, 15 December 2006]

12. Siemens, “Interference of FDD MS (macro) to TDD (micro)”, TSG RAN WG4#7 Tdoc 568/99, September 1999 [downloaded from http://www.3gpp.org/ftp/tsg_ran/WG4_Radio/TSGR4_07/Docs/Zips/R4-99568.ZIP (compressed), 15 December 2006]

13. Siemens, “Co-Siting of TDD/FDD and TDD/TDD Base Stations”, TSG RAN WG4#3, TSGR4#3(99)145, March 1999 [downloaded from http://www.3gpp.org/ftp/tsg_ran/WG4_Radio/TSGR4_03/Docs/Tzips/r4-99145.zip (compressed), 15 December 2006]

14. Siemens, “Summary of Results on TDD/FDD and TDD/TDD Co-Existence”, TSGR4#8(99) TDoc 653, October 1999 [downloaded from http://www.3gpp.org/ftp/tsg_ran/WG4_Radio/TSGR4_08/Docs/PDFs/r4-99653.pdf, 15 December 2006]

15. Siemens, “TDD/FDD Co-Existence Investigation”, 3GPP TSG RAN WG4#2 TDoc 53/99, February 1999 [downloaded from http://www.3gpp.org/ftp/tsg_ran/WG4_Radio/TSGR4_02/Docs/Tzips/R499-053.zip (compressed), 15 December 2006]

16. 3GPP, “Universal Mobile Telecommunications System (UMTS); Radio Frequency (RF) System Scenarios (3GPP TR 25.942 version 6.4.0 Release 6)”, 3GPP TR 25.942, March 2005

17. ITU, “Characteristics of Terrestrial IMT-2000 Systems for Frequency Sharing/Interference Analyses”, REPORT ITU-R M.2039, 2004

18. Nokia, “Simulation Results on TDD Local Area BS and FDD Wide Area BS Coexistence”, 3GPP TSG RAN W4#14, TSGR4#14(00)0966, Tdoc R4-000966, 2000 [downloaded from http://www.3gpp.org/ftp/tsg_ran/WG4_Radio/TSGR4_14/Docs/R4-000966.zip (compressed), 15 December 2006]

19. Motorola, “MWA Systems to FWA/NWA Systems Coexistence analysis in the 3.5 GHz band”, 36th meeting of PT SE 19, SE19(06)54, 5 September 2006.

20. Motorola, UK Broadband, Clearwire Denmark, WiMAX Telecom Europe, “Inter-System MWA MS to MWA MS Coexistence Analysis in the 3.5 GHz Band for Unsynchronized TDD Systems for TDD Adjacent to FDD Systems”, 37th meeting of PT SE 19, SE19(06)70, 17 November 2006.

21. ITU, “Mitigating Techniques to Address Coexistence between IMT-2000 Time Division Duplex and Frequency Division Duplex Radio Interface Technologies within the Frequency Range 2500-2690 MHz Operating in Adjacent Bands and in the Same Geographical Area”, REPORT ITU-R M.2045, 2005

22. Siemens, “Escape Mechanisms for the Case of FDD/TDD Co-Existence and TDD/TDD Co-Existence”, 3GPP RAN WG4#9, TSGW4#9(99)943, December 1999 [downloaded from http://www.3gpp.org/ftp/tsg_ran/WG4_Radio/TSGR4_09/Docs/Zips/R4-99943.ZIP (compressed), 15 December 2006]

23. Peng, M., Huang, B., Wang, W., “Investigation of TDD and FDD CDMA Coexistence in the Macro Environment Employing Smart Antenna Techniques”, *Communications, 2004 and the 5th International Symposium on Multi-Dimensional Mobile Communications Proceedings*, vol 1, pp 43–47, August 2004

24. Haas, H., McLaughlin, S., Povey, G., “Capacity-Coverage Analysis of TDD and FDD Mode in UMTS at 1920 MHz”, *Communications, IEE Proceedings*, vol 1, no 1, pp 51–57, February 2002

25. IEEE 802.16 Broadband Wireless Access Working Group, “Adjacent Frequency Block TDD/FDD Coexistence Scenarios for BWA”, 802.16cc-00/03, 18 January 2000 [downloaded from www.ieee802.org/16/tg2_orig/contrib/80216cc-00_03.pdf, 15 December 2006]

26. FCC, “Power and antenna height limits”, 47 CFR §27.50(h), 1 October 2005

27. ECC, “ECC Recommendation (04)05: Guidelines for Accommodation and Assignment of Multipoint Fixed Wireless Systems in Frequency Bands 3.4-3.6 GHz and 3.6-3.8 GHz”, Edition 160206 [downloaded from http://www.ero.dk/documentation/docs/doc98/official/pdf/REC0405.PDF, 8 December 2006]

28. FCC, “Emission limits”, 47 CFR §27.53(l), 1 October 2005

29. WCA, NIA and CTN, “In the Matter of Amendment of Parts 1, 21, 73, 74 and 101 of the Commission’s Rules to Facilitate the Provision of Fixed and Mobile Broadband Access, Educational and Other Advanced Services in the 2150-2162 and 2500-2690 MHz Bands (WT Docket No. 03-66 RM-10586); Part 1 of the Commission's Rules - Further Competitive Bidding Procedures (WT Docket No. 03-67); Amendment of Parts 21 and 74 to Enable Multipoint Distribution Service and the Instructional Television Fixed Service to Engage in Fixed Two-Way Transmissions (MM Docket No. 97-217); Amendment of Parts 21 and 74 of the Commission's Rules With Regard to Licensing in the Multipoint Distribution Service and in the Instructional Television Fixed Service for the Gulf of Mexico

(WT Docket No. 02-68 RM-9718)”, [downloaded from http://www.wcai.com/pdf/2003/fcc_Sept8.pdf, 11 December 2006]

30. FCC, “FCC Adopts Rules for Guard Band Manager Auction”, News Release, 9 March
2000 [downloaded from http://www.fcc.gov/Bureaus/Wireless/News_Releases/2000/nrwl0009.html, 11 December 2006]

31. Wacker, A., Laiho-Steffens, J., Sipila, K., Heiska, K., “The Impact of the Base Station Sectorisation on WCDMA Radio Network Performance”, *IEEE Vehicular Technology Conference (VTC 1999-Fall)*, vol 5, pp 2611–2615, September 1999

Appendix A Abstracts from Results of Literature Search

This appendix reproduces the abstracts from some of the documents found as a result of a literature search of studies that have been completed to date into the coexistence of FDD and TDD systems. Where an abstract is not available, a brief description of the document is provided:

Author(s): Rémi Chayer (TDD Coalition)

Title: Tutorial on TDD Systems – Part 3: Spectrum Allocation and Coexistence Issues

Source: Presentation delivered to FCC Office of Engineering and Technology, 3 December 2001

Comment: This presentation provides a general guide for FDD-TDD co-existence in terms of recommended practice, TDD-FDD collocation, general rules and practice, mitigation techniques and efficient spectrum allocations.

Author(s): Lee, T., L., Faure, C., Grandblaise, D.

Title: Impact of FDD/TDD Co-Existence on Overall UMTS System Performance

Source: Vehicular Technology Conference 2001 (VTC 2001 Spring) IEEE VTS 53rd, vol 4, pp 2655–2659, May 2001

Abstract: Interference and compatibility issues relating to coexistence of two duplexing modes in UMTS, FDD and TDD, are highlighted in this paper. Performance degradation due to co-existence is quantified by comparing with single system scenarios. It has been found that system performance depends on the loading of both FDD and TDD. Co-existence can be optimised when some compromise is observed. This optimal compromise has been derived in this paper, giving the maximum loading in one system when loading of another is known. BS↔BS interference scenario is found to be most damaging and therefore, the distance between BSs of the two systems should be maximised.

Author(s): Wilkinson, T., Howard, P.

Title: The Practical Realities of UTRA TDD and FDD Co-Existence and their Impact on the Future Spectrum

Source: Personal, Indoor Personal, Indoor and Mobile Radio Communications, 2004, PIMRC 2004, 15th IEEE International Symposium, vol 1, pp 22–26, September 2004

Abstract: This paper presents some of the first published results of real UTRA TDD and FDD equipment performance in respect of co-siting. The relevant 3GPP specifications are examined in detail to see whether they guarantee co-existence and if not whether they are exceeded in practice. In conclusion, the paper shows that the necessary performance to facilitate co-existence, co-siting and indeed antenna sharing has already been achieved in practice. These results not only have implications on the coexistence discussions for new spectrum allocations for 3G, such as the IMT-2000 extension band, but also on new standards for these.

Author(s): ITU

Title: Coexistence between IMT-2000 Time Division Duplex and Frequency Division Duplex Terrestrial Radio Interface Technologies around 2600 MHz Operating in Adjacent Bands and in the same Geographical Area

Source: REPORT ITU-R M.2030, 2003

Comment: In this Report the coexistence between IMT-2000 time division duplex (TDD) and frequency division duplex (FDD) radio interfaces are investigated. The interference properties between IMT-2000 CDMA Direct Spread (also called WCDMA or UTRA FDD) and IMT-2000 CDMA TTD (also called UTRA TDD) with its two modes high chip rate (HCR, 3.84 Mchip/s) TDD and low chip rate (LCR, 1.28 Mchip/s) TDD are studied for a large number of scenarios. Specifically, the BS-BS interference for both proximity and co-location scenarios are studied in the main part of the report, as well as the MS-BS, BS-MS and MS-MS scenarios are studied for proximity scenarios.

Author(s): Siemens

Title: Simulation Results on FDD/TDD Co-Existence Including Real Receive Filter and C/I Based Power Control

Source: TSGR4#6(99) 419, July 1999

Comment: This report is a follow on study of an earlier discussion of 3GPP on using an ideal receive filter and carrier-based power control for FDD/TDD co-existence on the 1920 MHz frequency border. This report provides new results including the impact of 'real' receive filters, C/I-based power control and it also proposes ACLR/ACS requirements for the UE and BS based on the simulation results.

Author(s): Qingyu, M., Wenbo, W., Dacheng, Y., Daqing, W.

Title: An Investigation of Interference between UTRA-TDD and FDD System

Source: Communication Technology Proceedings, 2000, WCC - ICCT 2000 International Conference on Communication Technology, vol 1, pp 339–346, August 2000

Abstract: Interference between the UTRA-TDD and FDD system is investigated. There are some specific interference modes in the TDD mode because the uplink and the downlink use the same frequency band in the TDD mode. The UTRA-TDD and the UTRA-FDD have severe adjacent channel interference if they use the adjacent carrier. Some simulations are done to study the interference. Impacts of four different interference instances were considered in the simulation. The impact on the UTRA-FDD uplink capacity is evaluated. Some interesting results are given from the simulations. The TDD and FDD base station can not be co-located if they use the adjacent frequency band between which the value of ACIR is below about 70 dB. The TDD and FDD cells can use the same frequency in some scenarios, which will increase the capacity, and utilize the underused UTRA-FDD uplink resources.

Author(s): Qingyu, M., Wenbo, W., Dacheng, Y.

Title: The Coexistence of UTRA-TDD and FDD System in the Adjacent Channel

Source: Global Telecommunications Conference, 2001, GLOBECOM 2001, vol 6, pp 3714–3718, November, 2001

Abstract: The coexistence of UTRA-TDD and FDD system in the adjacent channel is investigated in this paper. Different interference cases between the UTRA-TDD and FDD system are given. The UTRA-TDD and the UTRA-FDD have some adjacent channel interference if they use the adjacent carrier. Some simulations are done to study the interference and the Coexistence of UTRA-TDD and FDD system in the adjacent channel for the hierarchical cellular structure and the different ACIR value of BS-BS, MS-MS and BS-MS are taken into account.

Author(s): Siemens

Title: TDD/FDD Co-Existence - Summary of Results

Source: 3GPP TSG RAN WG4#3 Tdoc 96/99, March 1999

Comment: This report continues earlier investigations that were made to identify the ACP requirement for FDD/TDD coexistence on the assumption that 5 MHz carrier spacing is used and gives a more complete set of results based on extensive simulations.

Author(s): Siemens

Title: Interference of FDD MS (macro) to TDD (micro)

Source: TSG RAN WG4#7 Tdoc 568/99, September 1999

Comment: The co-existence of a macro cellular FDD and a micro cellular TDD system is investigated. The simulations cover the interference caused by a macro FDD MS towards both TDD MS and FDD MS and determines the ACLR/ACS requirements for the TDD modes in the HCS scenario.

Author(s): Siemens

Title: Co-Siting of TDD/FDD and TDD/TDD Base Stations

Source: TSG RAN WG4#3, TSGR4#3(99)145, March 1999

Comment: This is a follow on study of the previous work by Siemens submitted for 3GPP. The co-siting of base station is included in this report and the requirements for co-siting FDD/TDD systems are identified. Furthermore, filter solutions to fulfil the requirements are presented.

Author(s): Siemens

Title: Summary of Results on TDD/FDD and TDD/TDD Co-Existence

Source: TSGR4#8(99) TDoc 653, October 1999

Comment: This report collates and summarises the results of the numerous FDD/TDD co-existence simulations conducted by Siemens.

Author(s): Siemens

Title: TDD/FDD Co-Existence Investigation

Source: 3GPP TSG RAN WG4#2 TDoc 53/99, February 1999

Comment: This report summarises the results of extensive simulations performed to determine the probability of coupling losses in different environments, eg, macro, micro, pico.

Author(s): 3GPP

Title: Universal Mobile Telecommunications System (UMTS); Radio Frequency (RF) System Scenarios (3GPP TR 25.942 version 6.4.0 Release 6)

Source: 3GPP TR 25.942, March 2005

Comment: This document discusses system scenarios for UTRA operation primarily with respect to the radio transmission and reception and provides a comprehensive study of FDD/TDD co-existence. The scenarios are studied to define RF parameters and to evaluate corresponding carrier spacing values for various configurations.

Author(s): ITU

Title: Characteristics of Terrestrial IMT-2000 Systems for Frequency Sharing/Interference Analyses

Source: REPORT ITU-R M.2039, 2004

Comment: This report provides the baseline characteristic of terrestrial IMT-2000 systems for use in frequency sharing and interference analysis studies involving IMT-2000 systems and between IMT-2000 systems and other systems.

Author(s): Nokia

Title: Simulation Results on TDD Local Area BS and FDD Wide Area BS Coexistence

Source: 3GPP TSG RAN W4#14, TSGR4#14(00)0966, Tdoc R4-000966, 2000

Comment: This report studies the interaction between UTRA TDD indoor and UTRA FDD macro systems and thus investigates the possibility of UTRA TDD – UTRA FDD coexistence.

Author(s): Motorola

Title: MWA Systems to FWA/NWA Systems Coexistence Analysis in the 3.5 GHz Band

Source: 36^{th} meeting of PT SE19, SE19(06)54, 5 September 2006

Comment: This report presents simulation results for the scenarios of a Mobile Wireless Access (MWA) system interfering a Fixed Wireless Access (FWA)/Nomadic Wireless Access (NWA) system adjacent in frequency in 3.5 GHz band.

Author(s): Motorola, UK Broadband, Clearwire Denmark, WiMAX Telecom Europe

Title: Inter-System MWA MS to MWA MS Coexistence Analysis in 3.5 GHz band for Unsynchronized TDD Systems or TDD Adjacent to FDD Systems

Source: 37th meeting of PT SE19, SE19(06)54, 17 November 2006

Comment: This report studies MS-MS (SS-SS) interference using a statistical model based on certain hotspot definitions. The statistical MS-MS interference simulation considers the high user density areas (hotspots) instead of assuming uniform user distribution throughout the whole sector. It models the MS-MS interference problem in a more balanced manner than deterministic worst case analysis and statistical analysis using uniform distribution. In particular, this methodology effectively captures the two major intrinsic aspects of the MS-MS interference: i.) the event that two mobiles come close to each other occurs with certain probability and mostly happens in high user density areas, ii.) the power control scheme can scale down the Tx power of the interfering MS depending on its location relative to the base station. The report concludes that MS-MS interference is likely to be the critical scenario for deciding the guard band between a TDD MWA operator and FDD MWA operator.

Author(s): ITU

Title: Mitigating Techniques to Address Coexistence between IMT-2000 Time Division Duplex and Frequency Division Duplex Radio Interface Technologies within the Frequency Range 2500-2690 MHz Operating in Adjacent Bands and in the Same Geographical Area

Source: REPORT ITU-R M.2045, 2005

Comment: This Report considers techniques to improve compatibility between IMT-2000 TDD and FDD radio interface technologies operating in adjacent frequency bands and in the same geographic area. This report considers techniques, within specified classifications, to mitigate this interference and hence improve coexistence between TDD and FDD mobile networks in adjacent frequency bands and in the same geographic area. In so doing, this report describes the degree of improvement each techniques offers.

Author(s): Siemens

Title: Escape Mechanisms for the Case of FDD/TDD Co-Existence and TDD/TDD Co-Existence

Source: 3GPP RAN WG4#9, TSGW4#9(99)943, December 1999

Comment: This report discusses the co-existence of FDD/TDD in the case of non-coordinated, multiple operators and provides the escape mechanisms for coexistence.

Author(s): Peng, M., Huang, B., Wang, W.

Title: Investigation of TDD and FDD CDMA Coexistence in the Macro Environment Employing Smart Antenna Techniques

Source: Communications, 2004 and the 5th International Symposium on Multi-Dimensional Mobile Communications Proceedings, vol 1, pp 43–47, August 2004

Abstract: This paper investigates the impact of adjacent channel interference between TDD and FDD CDMA operators operating in macro environment. In the TDD-CDMA system, the smart antenna technique is employed and the performance is investigated and compared with the omni-directional antenna. Evaluation of TDD/FDD CDMA system coexistence is studied based on a static simulator. Intersystem interference impacts the capacity under various ACIRs (adjacent channel Interference ratios), the base station location offsets, and the cell radiuses are studied. Furthermore, the differences in impacting the capacity loss between the omni-directional and smart antennas are compared and analyzed. Results and conclusions are shown, which are useful for future CDMA cellular planning and frequency license allocation in 2 GHz.

Author(s): Haas, H., McLaughlin, S., Povey, G.

Title: Capacity-Coverage Analysis of TDD and FDD Mode in UMTS at 1920 MHz

Source: Communications, IEE Proceedings, vol 1, no 1, pp 51–57, February 2002

Abstract: In the Universal Mobile Telephony System (UMTS) the frequency division duplex (FDD) and time division duplex (TDD) modes have adjacent carriers at 1920 MHz. This creates adjacent channel interference (ACI) between the two different air interfaces. Since different duplexing modes are used, the implications for each system are different, with respect to capacity and coverage: these implications are investigated. The separation distance of the TDD and FDD base station and the load in each system are varied and a symmetrical speech service in both systems is considered, with non-ideal power control assumed. It is found that for an FDD cell radius of 1000 m, a TDD cell radius of 50 m and 10% maximal tolerable outage, the effects of ACI on capacity can be compensated by dynamically increasing the required power at each BS, without affecting the coverage.

Author(s): IEEE 802.16 Broadband Wireless Access Working Group

Title: Adjacent Frequency Block TDD/FDD Coexistence Scenarios for BWA

Source: 802.16cc-00/03

Comment: Same area-adjacent frequency block system coordination will be a requirement for coexistence of BWA systems. Adjacent carrier interference mitigation may require frequency guard bands, polarization discrimination and substitution of sector frequency assignments. This report examines one example of the coordination issues that need to be considered. A TDD system is selected as the interference source and an FDD system is specified to be the victim. Interference simulation estimates indicate that the reserve carrier assignments that can be made available with some TDD frequency re-use plans are very effective as a coexistence resolution technique.

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