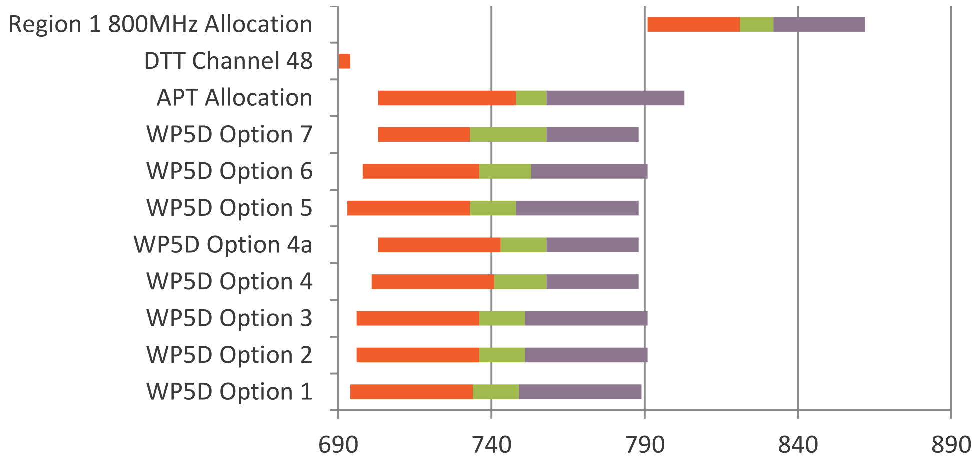
Terminal capabilities in the 700 MHz band

Final report for Ofcom



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independent wireless experts

About Real Wireless

Real Wireless is a leading independent wireless consultancy, based in the U.K. and working internationally for enterprises, vendors, operators and regulators – indeed any organization which is serious about getting the best from wireless to the benefit of their business.

We seek to demystify wireless and help our customers get the best from it, by understanding their business needs and using our deep knowledge of wireless to create an effective wireless strategy, implementation plan and management process.

We are experts in radio propagation, international spectrum regulation, wireless infrastructures, and much more besides. We have experience working at senior levels in vendors, operators, regulators and academia.

We have specific experience in LTE, UMTS, HSPA, Wi-Fi, WiMAX, DAB, DTT, GSM, TETRA – and many more.

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0. Executive Summary

A new mobile band allocation is anticipated in Region 1, including Europe and the UK, in the 700MHz band adjacent to frequencies that would remain in use by digital terrestrial television (DTT). However the bandplan is not yet fixed and depends on a number of factors, including the ability of manufacturers to provide mobiles which efficiently support the band. This study is to understand the ability of mobile terminals to make use of the mobile band given the emission limits required to protect DTT receivers from interference and given the impact worldwide economies of scale. For this study Real Wireless has been supported by Benetel and Rethink Research, working independently of vendors and operators on behalf of Ofcom.

The 2012 ITU World Radiocommunication Conference (WRC-12) adopted a resolution "to allocate the frequency band 694-790 MHz in Region 1 to the mobile, except aeronautical mobile, service on a co-primary basis with other services to which this band is allocated on a primary basis and to identify it for IMT", effective immediately after WRC-15 [1]. This band is usually referred to as the 700 MHz band.

The APT (Asia Pacific Telecommunications) community agreed to adopt a band plan [2] for the 700 MHz band which has since been designated as 3GPP Band 28 (for FDD) and Band 44 (TDD). This APT bandplan provides an additional allocation of 2x45MHz (FDD) or 100MHz (TDD) for mobile communication, including IMT.

At the next WRC in 2015 member states in Region 1 including European member states must be ready with an agreed band plan for 700 MHz. The work underway within CEPT, notably Conference Preparatory group Project Team D, has been examining the different channelling arrangements that have been proposed [3]. These draft options are shown in Figure 10-1 together with the existing region 1 800MHz allocation, the APT FDD allocation and the upper edge of DTT Channel 48. Adopting any of these proposed 700MHz options would require use of some DTT channels above channel 48 to be changed from existing DTT broadcasting to mobile.

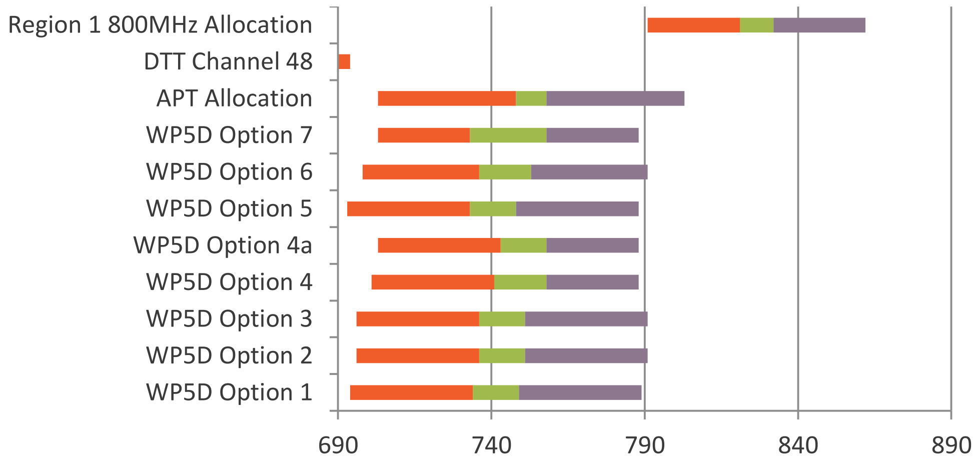

Figure 0-1: Band plan options for the proposed European 700 MHz band

The study found there is a wide variation in out-of-band (OOB) emission limits to protect DTT from across the different sources including APT, CEPT and 3GPP as shown in table 0-1. The CEPT 030 limits are clearly the most stringent compared to the APT and 3GPP and arise from minimum coupling loss calculations using worst case scenarios.

Source	dBm (6 or 8 MHz)	dBm/MHz
UK/CEPT OOB value 1 (I/N = -6dB)	-52.6 (8 MHz)	-61.6
UK/CEPT OOB (I/N = -10dB)	-58.6 (8 MHz)	-67.6
3GPP OOB B28	-26.2 (6 MHz)	-34.0
CEPT 030 (800 MHz)	-65 (8 MHz)	-74.0
APT Rep 24 OOB	-26.2 (6 MHz)	-34.0

Table 0-1: User Equipment (UE) OOB limits defined by various bodies for different 700MHz bandplans

We have derived a refined set of bandplan options based on the band plan configurations since one of them (option 3) overlaps with channel 48 and therefore was discounted as an option. Key variations are the separation from the top of the DTT band at channel 48, the channel bandwidth and the duplex gap.

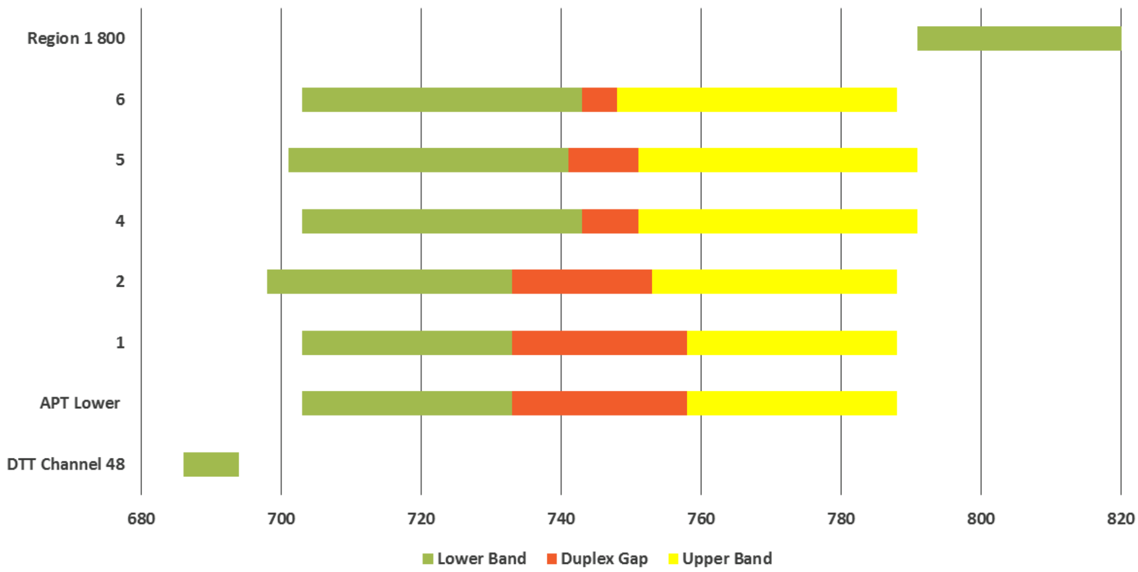

Figure 0 -2: Final band plan options considered in this study

The preferred two band plan options that can meet the stringent protection limits to protect DTT are:

1. Option 1: 2 x 30 MHz compatible with the APT700 bandplan
2. Option 4: 2 x 40 MHz an EU specific variant which offers more usable spectrum but which we believe can be efficiently accommodated in terminals

In particular, option 4 requires a dual duplexer in the terminal and overlaps with APT700 in the lower duplex. However, this results in a 10 MHz overlap between lower and upper duplex subbands compared to APT which has a 20 MHz overlap.

This study addresses a number of specific questions posed by Ofcom regarding the terminal capabilities that could support one or more of the proposed band plans whilst striving to protect DTT services and containing the cost impact of doing so.

The study has been summarised against the key aspects that will impact any decision on adopting a particular band plan for 700 MHz. The table below provides an overview of the level of harmonisation and recommendation for each of the considered bandplan options.

Band plan option	Available spectrum	Degree of harmonisation	Incremental difference from today	Recommendation
1 – 703-733 MHz paired with 758 – 788 MHz	2 x 30 MHz	Full harmonisation with APT700 lower duplex	Need for inclusion of filters that achieve 45 dB rejection into DTT	This bandplan is a viable option based on the achievable frequency separation, the use of current filter technology and ability to achieve 45 dB attenuation to protect DTT services. This will also provide harmonisation with APT 700 frequencies
2 - 698-733 MHz paired with 753 – 788 MHz	2 x 35 MHz	Partial harmonisation with APT700 lower duplex (703 MHz- 5 MHz)	Depends on number of cascaded filters needed to meet 45 dB rejection into DTT	This is not a viable option due to the small transition band and filter implementation cost and complexities
3 - -693 – 733 MHz paired with 748 – 788 MHz	2 x 40 MHz	Partial harmonisation with APT700 lower duplex (703MHz – 10 MHz)	See recommendation	This is not a viable option as it overlaps with DTT and so is not considered further in the report
4 - 703-743 MHz paired with 751 – 791 MHz	2 x 40 MHz	Partial harmonisation with APT700 lower duplex except for an addition 10	Need for a dual duplexer and for inclusion of filters that achieve 45 dB rejection into DTT	This bandplan is a viable option and is attractive as it allows 2 x 40 MHz thus maximising spectrum availability.

Band plan option	Available spectrum	Degree of harmonisation	Incremental difference from today	Recommendation
		MHz above 733 MHz		This overlaps the APT 700 band plan with the lower duplex part in principal could support global roaming
5 - 701-741 MHz paired with 751 – 791 MHz	2 x 40 MHz	Partial harmonisation with APT700 lower duplex (703 MHz- 2 MHz)	Need for FBAR filter and dual duplexer to achieve 45 dB rejection with on 7 MHz frequency separation	This is the costliest implementation as it requires FBAR filter technology but is feasible and uses the whole 2 x 40 MHz bandwidth effectively.
6 - 703- 743 MHz paired with 748 – 788 MHz	2 x 40 MHz	Partial harmonisation with APT700 lower duplex except for an addition 10 MHz above 733 MHz	Need dual duplexer (See recommendation)	This is not a viable option due to switching complexity which would limit harmonisation achievable. 5 MHz duplex gap is not sufficient for the BS to isolate the TX/RX paths

Table 0-2: Summary matrix of bandplan options

The key findings from this study are summarised below against the five specific questions posed by Ofcom.

Adjacent band coexistence and in band performance

Ofcom wanted to understand the possible adjacent band co-existence and in-band performance implementation considerations. In particular in relation to achieving a certain level of unwanted emissions into DTT channel 48 that can be achieved from a mobile terminal.

The performance of mobile devices in response to the different bandplans is heavily influenced by the cost/performance tradeoffs associated with the technology used to implement dual duplex filters in the mobile receiver. We found that the OOB emission limits proposed by the UK/CEPT can be achieved using current filter technology so long as there is a 9 MHz frequency separation i.e. a stopband starting at 703 MHz. Two out of the four filter vendors we interviewed being able to achieve this with current filter technology SAW/BAW. Those manufacturers also believed that a 6 MHz frequency separation could be achieved using FBAR technology, which is somewhat more expensive but likely to reduce in cost over time.

Table 0-3 provides an assessment of the overall performance of the feasible options in each band using different technologies. It is based on Real Wireless estimates and inputs from filter manufacturers and is subject to the assumption that devices have to achieve the conservative protection requirements of DTT consistent with the UK submission to CEPT [4]. Costs are estimates of the selling price from filter manufacturers at today's prices and assuming handset volumes commensurate with the scale of the European market.

	Option 1 (SAW)	Option 1 (FBAR)	Option 2 (FBAR APT+5MHz)	Option 3 (overlaps DTT)	Option 4 (FBAR Dual Duplexer)	Option 4 (Dual Duplexer)	Option 5 (SAW, not realisable	Option 5 (FBAR Dual duplexer)	Option 6 (SAW Dual Duplexer)	Option 6 (FBAR Dual Duplexer)
Bandwidth	2x30	2x30	2x35	2x35	2x40	2x40	2x40	2x40	2x40	2x40
Commonality with band 28 lower duplex	2x30	2x30	2x30	2 x 30	2x30	2x30	2x30	2x30	2x30	2x30
Re-use of band 28 lower duplex filter	Yes	Yes	No	No	No	No	No	No	No	No
Achievable suppression	5 to 45	45	No	No	5 to 45	45	No	45	5 to 45	45

Table 0-3: Band Plan Options Performance Matrix given UK/CEPT requirements

Dual duplexer implementation

Ofcom wanted to understand how a dual duplexer might impact the number of supported bands in a mobile terminal, particularly since a dual duplexer is required in a 2 x 40 MHz configuration.

We found that, similar to designs compatible with the APT700 2 x 45 MHz band, a dual duplexer filter is required for 2 x 40 MHz. Each additional duplexer has a similar complexity and cost as supporting an additional band. High end modern handsets can support up to 4 GSM, 5 WCDMA and 13 LTE bands. Integrated solutions are now being developed to facilitate the inclusion of multi-band multi-mode front end designs which would reduce the incremental cost per added band.

Developments in current technology allow for the inclusion of a dual duplexer in a multi-band environment into a single handset. This assumes sufficient ports on the Radio Frequency Integrated Circuit (RFIC) and available ports on switches. However, the cost drivers will encourage the use of only the most attractive bands in future lower end phones.

Impact to the performance of a terminal in existing bands

Ofcom wanted to understand if there would be any impact on the performance of a terminal in existing bands if the European channelling arrangement for 700 MHz did not align with the APAC channelling arrangement and therefore had to be implemented separately in the terminal.

Adding 700 MHz capability to a multi-band handset is unlikely to impact on performance given proper design. This is because the isolation provided by a high isolation (30 dB) low loss band switch (0.45 dB with a Single Pole Six throw (SP-6T) and 0.50 dB for SP-8T) would isolate the existing bands from any additional band and the insertion loss would be no greater than with fewer bands assuming one band is assumed to be active at any one time.

In order to determine the level of industry support for an added European 700 MHz band we conducted a market analysis based on interviews with over 20 vendors and operators from across the industry:

- We note that industry group Digital Europe and one of the filter manufacturers support the adoption of the APT700 as band for use across Europe based mainly on the global harmonisation benefits
- The majority of the handset makers, predictably, support the adoption of APT700, which would improve their economics.
- However, less than half of original equipment manufacturers (OEMs) interviewed would consider supporting an EU-only band (i.e. a band that was not compatible with APT). Vendors with a European focus would still support the band, but potentially in only a few handset models. Consumers would have a smaller choice of handsets than those in other regions

Financial cost against different 700 MHz band plan options

Ofcom wanted to understand the financial cost of adding filters against different 700 MHz band plan options for a handset which have not been published. In this study we examined these costs and other aspects that can impact the decision by a vendor of adding new bands to mobile devices.

The relative cost to handset vendors of adding a new band to a UE is that of a higher complexity SAW or BAW filter and a SAW diversity receive filter, assuming that sufficient RF ports are available on the RFIC, sufficient switch ports are available and that an existing power amplifier can support the new band. If a new power amplifier is needed this would add an amount equivalent to a higher complexity SAW Duplexer for a single PA.

From an R&D standpoint components such as switches and power amplifiers are already available to support the 700MHz band. This means the duplexers and RX filters are the components that will need to be developed for the new European 700 MHz band but these are within the scope of capability of several manufacturers using current technology. The likely spend in areas such as design time (including simulation), test wafer, component prototype, testing, heat cycling etc will be R&D spend but unlikely to be significant relative to adding any other new component.

Regarding the UE development, if Band 28 is already supported with a dual duplex implementation and the 30MHz option 1 is chosen then the R&D costs are not expected to be significant.

Handset vendors may be concerned about the total bill of materials cost (BoM), rather than the minor component costs of an additional filter. For a high end device that supports multiple bands the price of a filter is negligible compared to the additional co-existence verification with other bands i.e. integration and testing that is associated with adding a new band to a handset. Handset vendors would likely see this as a market decision. That decision will not be a simple one of volume and retail price but will be influenced by operator commitment – how far an operator will pay a premium, or commit to marketing activity, or to subsidies, to secure a 700MHz device. As a result many operators around Europe have expressed support for a harmonized bandplan so they can access handsets that are already developed.

From the perspective of a large handset vendor, there is opportunity cost related to support for a regional or specialized band, such as EU700. Most vendors will focus their investment budgets first on the major global bands, where the largest return is likely to be realized. In the case of lesser bands, most will support only a selection of the total available. Therefore, if EU700 were selected there would be the opportunity cost of not supporting another regional band becoming available in the same timeframe (e.g. USA AWS-3 or BAS bands). OEMs will make a market based decision to select the regional bands with the largest projected return but very few will support all the options. Given that there are existing sub-1GHz bands available for LTE in Europe, EU700MHz may seem a poor choice compared to an emerging band in a high growth region (e.g. a new Chinese regional band). The opportunity cost of neglecting a high growth option in favour of EU700 would be significant, though might still be justified for a vendor with high reliance on the EU market. However, more clarity on which regional bands will be opened up by 2018 – i.e. the choices available to OEMs - would be needed to provide a full opportunity cost assessment for adopting EU700.

In terms of harmonisation between the European bandplan options and the APT700 band plan, only full harmonisation would achieve economies of scale for EU 700 handsets. The caveat in this case would require handsets developed for the APAC region would need to adopt the use of filters complying with more stringent EU limits. If option 1 frequency bandplan is adopted in Europe then this could create a new harmonised, global mobile band (except US) using existing technology and small, if any, additional cost.

If Europe decides to adopt a bandplan that is partially harmonised with the APT700 band then it is possible the resulting 700 MHz band in Europe may not be attractive to European operators, especially if they perceive that they have sufficient sub 1 GHz spectrum already. However, Ofcom, Real Wireless and others have illustrated the potential growth in demand for mobile traffic in future. This demand is also likely to be consumed in locations where 700 MHz would be of much benefit i.e. deep indoors and rural areas. Therefore, we note that there will be a continued need for more spectrum and thus even if a European ecosystem emerges the spectrum will be of some value to European operators based on the expected growth in mobile traffic demand. The perceived value of this spectrum and availability of handsets is likely to be increased if any European variant is aligned with Africa.

The bandplan options considered in this study show there are two leading options that provide the most attractive benefits in terms of:

- Spectrum availability and usability
- Viable cost of new filters for the development of today's handsets
- Harmonisation with APT700

Options 1 and 4 both offer the types of benefits that will satisfy the both national regulators across Europe and vendors alike to some degree. In order to satisfy regulators, the handsets must include filters that can achieve the additional suppression into the DTT band and optimising the quantity of usable spectrum e.g. assuming 2 x 40 MHz is preferred over 2 x 30 MHz. Depending on which option is chosen, for example, in the case of option 1 pressure on vendors to use those filters that protect DTT, which are available today deployed in their new handsets could result in an almost globally harmonised 700 MHz band and achieve significant economies of scale. In the case of option 4 the same set of filters are required to protect DTT and partial harmonisation with the APT700 band (an addition 10 MHz beyond the APT700 lower duplex). However, the cost increases due to the inclusion of a dual duplexer. This may result in a less attractive proposition for vendors due to the extra cost of a dual duplexer and therefore dilutes the amount of pressure slightly that can be placed on vendors to support a regional variant of the 700 MHz band in Europe.

There is a clear trade-off between option 1 which provides a universally harmonised band with little additional cost to vendors, against option 4 which is a little more costly to vendors but provides significantly greater spectrum for mobile use.

The development of a mobile handset ecosystem that can use a suitable European 700MHz band-plan, whilst providing adequate protection to DTT, and make good use of scarce spectrum, is both a technical and a market issue. This study has demonstrated that it is feasible to develop a European bandplan that would allow 2x40 MHz mobile operation whilst protecting DTT at stringent limits (ie utilise 83% of the frequencies between 694 and 790 MHz) for a small incremental cost per handset. However this study has not been able to demonstrate that such frequency use would be more desirable than using either a EU 2x30MHz allocation which has the same frequency limits but more stringent OOB emissions as the APT700, or to accept interference into channel 48 and accept the use of APT700 (including their relaxed limits and more interference into channel 48). The technical issues can be solved with current technology – but the market issues, including the value of facilitating a new, global sub 1 GHz harmonized band are less clear.

If Europe were to adopt the APT-700 bandplan (including its more relaxed limits) would only allow use of 2x30MHz (63% of the available spectrum), and cause more interference into channel 48. Using the same frequencies but with stringent limits that would protect European DTT would mean that the European bandplan would have to differ from that implemented by APT countries – it is unlikely that many low cost handsets in Asia would adopt the marginally more expensive filters to achieve more stringent European limits. Hence, even using the same frequency allocation with different OOB limits would result in a non-harmonised band.

1. Introduction

The following report has been produced by Real Wireless for Ofcom to examine the capability of mobile terminals to support a variety of 700 MHz frequency bandplan configurations.

In the UK, it is Ofcom's duty to prepare and define its future spectrum strategy and policy to support a new mobile band allocation for Europe and the UK, in the 700MHz band. However, the proposed frequency allocation is 694-790 MHz which is adjacent to frequencies that would remain in use by digital terrestrial television (DTT). However the bandplan is not yet fixed and depends on a number of factors, including the ability of manufacturers to provide mobiles which efficiently support the band.

This study is to understand the capability of multi-band mobile terminals, in particular the technology, performance and cost to make use of the mobile band given the emission limits required to protect DTT receivers from interference and given the impact worldwide economies of scale.

The 2012 ITU World Radiocommunication Conference (WRC-12) adopted a resolution "to allocate the frequency band 694-790 MHz in Region 1 to the mobile, except aeronautical mobile, service on a co-primary basis with other services to which this band is allocated on a primary basis and to identify it for IMT", effective immediately after WRC-15 [1]. This band is usually referred to as the 700 MHz band.

The APT (Asia Pacific Telecommunications) community agreed to adopt a band plan [2] for the 700 MHz band which has since been designated as 3GPP Band 28 (for FDD) and Band 44 (TDD). This APT bandplan provides an additional allocation of 2x45MHz (FDD) or 100MHz (TDD) for mobile communication, including IMT. These offer for the possibility of a globally harmonised 700MHz mobile band, but such harmonisation must accommodate the wide variation in the timing, bandwidth and protection requirements of existing services in this band, especially the TV service.

At the next WRC in 2015 member states in Region 1 including European member states must be ready with an agreed band plan for 700 MHz. The work underway within CEPT notably Conference Preparatory group Project Team D have been examining the different channelling arrangements that have been proposed [3]. These draft options are shown in Figure 1 together with the existing region 1 800MHz allocation, the APT FDD allocation and the upper edge of DTT Channel 48. Adopting any of these proposed 700MHz options would require use of some DTT channels above channel 48 to be changed from existing DTT broadcasting to mobile. Making equipment that can span the full 2x45MHz APT allocation is difficult with current technology and practical implementations appear to use an overlapping 30MHz dual duplexer arrangement to span the 45MHz uplink (or downlink) bandwidth. Some of the bandplan options proposed by Europe may also require a dual duplexer implementation and this study examines the filter technology that can support the various options.

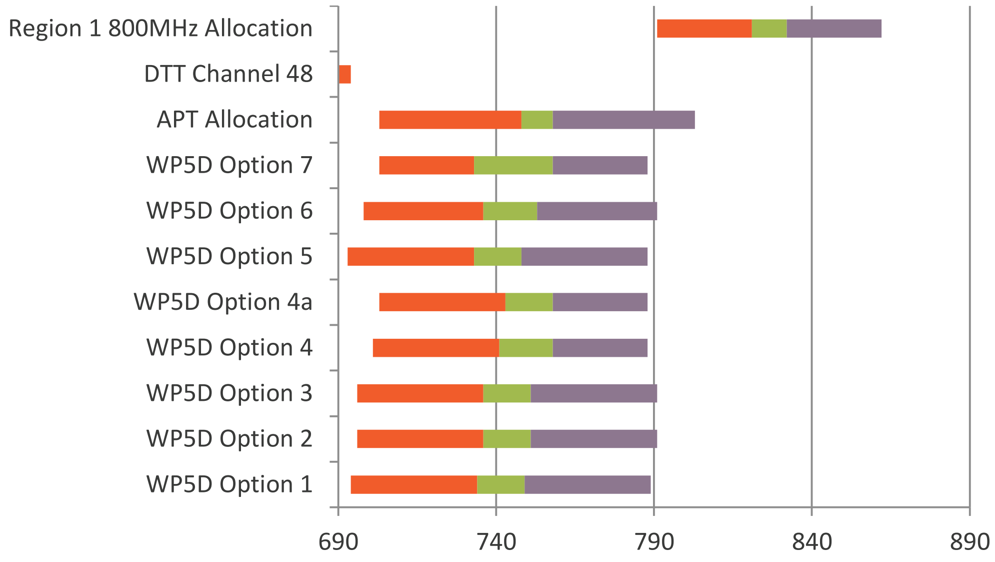

Figure 1: Frequency arrangement of the 700MHz bandplan options being considered by CEPT CPT-D, the 800MHz IMT allocation in Region 1 and DTT Channel 48.

There is clearly some incompatibility with the proposed options which include:

- The APT bandplan extends 12MHz into the 800 MHz lower subband (used for downlink);
- The APT lower duplexer is 9MHz above DTT Channel 48. Many of the options proposed above are even closer to the DTT channel and may not provide sufficient protection to channel 48.

The opportunity to have a globally harmonised mobile band could allow lower complexity (cost) user equipment (UE) mobile devices to operate globally and increase the market size for suitable components.

UEs need to be able to support services in a range of different bands, and a range of different technologies. Operators who often subsidise these devices would seek to ensure commonality as much as possible across their global service footprint. Supporting more bands in any given device can add complexity and/or cost and some combinations of available bands may not be supported by all operators reducing the utility of a frequency allocation. Different adjacent uses of spectrum can constrain the technical co-existence conditions and adoption of technical standards developed in one region may cause unsatisfactory interference in another region.

For FDD operation in 700 MHz, five main bandplan alternatives that bracket the range of options considered by WPD have been identified by Ofcom and are:

1. 703-733 MHz (uplink) + 758-788 MHz (downlink) – APT lower duplex
2. 698-733 MHz (uplink) + 753-788 MHz (downlink) – APT + 5 MHz below
3. 693-733 MHz (uplink) + 748-788 MHz (downlink) – APT + 10 MHz
4. 703-743 MHz (uplink) + 751-791 MHz (downlink) – new 2x40 MHz proposal
5. 701-741 MHz (uplink) + 751-791 MHz (downlink) – new 2 x 40 MHz proposal

Since option 3 overlaps with Channel 48, it will not be considered further in this study. Real Wireless, working with its partners Benetel and Rethink Research, has been asked to investigate variants 1, 2, 4 and 5 from the above. In particular to help inform Ofcom on the technical equipment performance constraints and market issues which can constrain equipment availability:

For these bands Ofcom have requested:

- An investigation of the technical, regulatory and commercial trade-offs in adopting a particular bandplan;
- Understanding of the implications of the work undertaken by CEPT and 3GPP;
- Understanding and translation into practical implementations into in-band and out of band performance;
- Understanding of the financial and market costs of developing multi-band terminals with different levels of compliance with existing bandplans.

This final report addresses each of the work packages and provides the relevant analysis against each of the issues raised by the scope of the study. The structure of the report is as follows:

- Chapter 2 provides the output of a literature survey of the research used to derive Out-of-Band Limits adopted by 3GPP (band 28) and APT 700MHz bandplans.
- Chapter 3 provides analysis of the technical aspects of realising practical filters for different optional bands.
- Chapter 4 provides market analysis which captures and addresses the market and ecosystem related issues in realising the practical filters by 2018 within vendors' handsets.
- Chapter 5 addresses explicitly all of the questions that were posed by Ofcom for the study.

Real Wireless would like to acknowledge all the filter manufacturers support and information to help us meet the technical objectives of the study. We would also like to acknowledge the support from all the handset vendors and operators that took part in our market analysis.

2. Mobile terminals must include 30 dB more suppression to protect European DTT services

This chapter discusses the requirement for additional attenuation at the DTT band edge 694 MHz and below as specified by the UK input to the CEPT to protect DTT services. The following sections capture the summary of the various studies and simulations conducted across different regions such as Asia Pacific region (ITU Region 3) and 3GPP which has a global membership and Europe through the CEPT.

It is the APAC community that has already established a band plan (2 x 45 MHz) and a set of Out of Band emission limits which have been incorporated into the latest 3GPP standards which are discussed further in the sections below.

2.1 Derivation of the APT limits

APT has derived their recommendations for the OOB UE limits based on the following set of documents:

- APT/AWF/REP-11 (Sept 2009) [5] - UHF band usage and considerations for realising the UHF digital dividend: This document identifies areas to study to develop the 700MHz bandplan including duplex direction, centre gap, self de-sensitisation, multi-band opportunities and handset complexity.
- APT/AWF/REP-14 (Sept 2010) [6] – Harmonised frequency arrangements for the band 698-806 MHz – this document notes that a centre gap as small as 8MHz may not be achievable and notes that a pragmatic solution would be to use 2x45MHz, with a 10MHz gap. It further notes that a dual-duplexer is likely to be needed for any practical implementation. The identification of OOB limits were deferred for further study;
- APT/AWG/REP-24 (Sept 2011) [7] – Implementation issues associated with the use of the band 698-806 MHZ by mobile services. This is the key document to identify the technical constraints and OOB emission levels, based upon a series of simulations.
    - This report based its findings upon a series of deterministic (minimum coupling loss-based), probabilistic (Monte Carlo based) , and empirical studies (practical measurements);
    - A range of different values for different cases emerged – and the protection ratios used are not clear;
    - It concluded that the probability of interference to adjacent DTT will be low when the UE maximum OOB emissions are between -30 and -40dBm/MHz across the DTT receive band, and considering technical and economic factors the UE OOB limits were set to -34dBm/MHz.

Below we provide an overview of some of the particular technical factors within each of these reports.

2.1.1 APT/AWF/REP-11 (Sept 2009) – UHF band usage and considerations for realising the UHF digital dividend

This report identifies the fundamental study areas required to develop the 700MHz bandplan. It focuses on the duplex direction, the size of the centre gap, self de-sensitisation and multi-band opportunities. In particular the study highlights the generic constraints which might have an impact on the realisation of the digital dividend across the APT community such as:

- Analogue television still in use across some countries
- DTT has been introduced but using different standards across the APT community e.g. DVB-T, ATSC and ISDB-T and the interference can vary in each case
- Some frequencies will not be available for DTT before analogue switch off
- Some APT countries also use the band for other terrestrial services besides broadcasting that require protection

The study identifies the corner frequencies for the 700 MHz i.e. 698 MHz – 806 MHz and proposes a number of configurations/views based on the US and other more conventional arrangements with the lower block identified as uplink and upper block as downlink.

In addition, this report introduces the dual duplexer requirement based on current RF filter technology only able to support around 30-35 MHz bandwidth given the 2 x 45 MHz bandwidth proposal. There are little specific new technical co-existence parameters given in this report, but rather reference material used to inform the discussion points.

2.1.2 APT/AWF/REP-14 (Sept 2010) – Harmonised frequency arrangements for the band 698-806 MHz

It is in this document that the APT community make the proposals for the actual frequency arrangements and associated parameters. Noting the identification of 698 MHz – 806 MHz from WRC’07 as a band for IMT systems, the APT community commenced their proposals on the key considerations for frequency arrangements based on:

- Efficient usage of spectrum
- Maximum spectrum block size
- Appropriate protective measures for services in the adjacent bands

A summary of the proposals is identified below:

- A lower guard band of 5 MHz should be allocates between 698 – 703 MHz
- An upper guard band of 3 MHz should be allocated between 803-806 MHz#
- 10 MHz centre gap
- 2 x 45 MHz bandwidths FDD
- 1 x 108 MHz TDD

This short report essentially establishes the key technical parameters and frequency/duplex configuration and guard bands.

2.1.3 APT/AWG/REP-24 (Sept 2011) – Implementation issues associated with the use of the band 698-806 MHZ by mobile services.

This document presents the technical constraints and OOB emission levels, based upon a series of simulations conducted by the APT community.

We provide a critique of the technical parameters, simulation set up and analyses conducted by APT in order to verify whether a pragmatic approach has been taken.

The study includes a series of deterministic (MCL-based), probabilistic (Monte Carlo based), and empirical studies (practical measurements). Each set of separate studies adopts a technique and analysis appropriate to determine either:

- Probability of interference into DTT services (exceed Rx threshold levels)
- Worst case values in order to stimulate more detailed investigation

The possible interference scenarios considered were as expected for protecting DTT reception as it included all possible eventualities for a mobile terminal interfering with an outdoor antenna and an indoor antenna.

A number of methodologies for calculating interference were used such as Minimum coupling loss, Monte Carlo analysis and empirical studies. The type of analysis that can introduce some uncertainty is the Monte Carlo analysis, therefore we analyse the approach and parameters in more detail.

The system level simulation used the following set up:

- LTE UE standard parameters in accordance with 3GPP TS 36.101
- Propagation model as per ITU-R SM 2028 (UE to DTV Rx) modified Hata
- LTE UEs randomly dropped in the given density of 18 UE per km^2
- DTV receivers are located on a grid of 50 m separation or 100m x 100m grid
- Interference into the DVB-T, ATSC and ISDB-T standards are considered
- Output shows probability of DTV outage

The study included two simulations using Monte Carlo analysis which adopted the random distribution of UEs in the appropriately sized grid squares. The Seamcat tool was used which is a standard tool adopted by many regulators to calculate co-existence analysis. In one of the simulations the parameters and set up was conducted using 3GPP 36.942 [8], which is used for simulating the performance of LTE which may not be considered suitable for a co-existence study but provides realistic technical parameters and conditions for setting up a mobile network. The parameters agreed by the Correspondence Group[1] are used in the simulations suggesting some consensus around which parameters are to be used.

There does not seem to be analysis in the time domain in terms of percentage time of interference but only on the location of interferers. Although an added dimension, interference analysis which incorporates the time domain, will provide a useful (although

[1] The Correspondence Group is assumed to be the a set up to discuss technical parameters for co-existence between mobile and broadcast services across the APT community

more complex) statistical spread of the DVB-T service outage caused by UE interference. A time based model would be necessary if there are environments in which a repeatable set of interference scenarios are difficult to predict. For example, if mobile TV was the victim receiver.

We consider that the assumptions and set up used across all the different probabilistic studies captures the essential interference parameters. In addition, the technical parameters for DVB-T are also aligned with the relevant specifications such as ITU-R BT 419 [9], for receive antenna directivity discrimination and antenna polarisation discrimination. The ACS is calculated from ITU-R WP 5D calculations based on SNR and protection ratios [10].

2.2 Ongoing definition of limits within CEPT

Work commenced in CEPT after the WRC'12 on the bandplan arrangement for the 700 MHz band. Key documents have been submitted to CEPT WPD5 to help inform appropriate technical limits for use of this band considering existing and future uses. Some of these documents differ markedly in their recommendations.

The following are considered key:

- Input from Germany on issues to consider developing a 700MHz bandplan [11].
- Input from UK identifying OOB UE limits to avoid interference to DTT [12] ;
- EBU document broadly supporting the UK input [13]
- GSMA input document critical of the above UK input [14]
- GSMA document proposing preferred IMT frequency arrangements [15]

The main issues identified in the German input document [11] are high level considerations identifying key aspects to be considered and the wide variability of the limits set by APT and the definition of the 800MHz OOB emissions. It identifies:

- some of the key constraints in developing a new bandplan for 700MHz, including the size of the guard band, duplex gap, benefits of harmonisation, feasibility of implementation, spectrum efficiency and OOB emission limits;
- that 2x40MHz can use 83% of spectrum, whereas 2x30 can use as little as 63%;
- the 800MHz allocation uses an 11MHz duplex gap.
- It notes that the OOB emission limit proposed by CEPT for 800MHz is -65dBm/8MHz in accordance with ITU-R BT 1368-9 – which is 6-7dB more stringent than the current CEPT 700MHz proposal of -58.6dBm/8MHz, but approximately 40dB more stringent than the APT proposal.

The UK input document uses RF parameters identified in [16] and DTT characteristics defined in [17] and a minimum coupling loss analysis to identify UE Out of Band Limits to protect DTT networks. Key assumptions in the analysis are:

- Two limits are derived based upon external interference to noise ratios of -10dB and -6dB;
- The UE is assumed to be transmitting at full power (23dBm), at minimum possible coupling loss to a rooftop antenna;
- The DTT ACS is assumed to be 80dB based upon inserting an additional filter with 9MHz separation between DTT and the lowest frequency of the mobile band –

sometimes referred to as an 18MHz offset (offset between the middle of DTT and Mobile channels using 8MHz DTT BW, 9MHz gap, 10MHz LTE BW). Additional filtering at 18MHz adds further 32dB isolation (ACS additional filtering);
- Link budget analysis derives the UE OOB limits based on assumed levels of ACS and derived values of UE ACLR (of 78.68 dB) – which does not compare favourably to the ACLR of only 32.2 dB from ITU-R BT.2033 Table 7 [18].
- Implied in the analysis is that the DTT receiver is at the edge of DTT range, DTT receiving DVB-T2 256-QAM (most sensitive signal) – but no values are given for reference sensitivity – analysis is performed on the basis of the maximum permitted rise above the noise floor.

The EBU input document is broadly supportive of the UK input and derives similar values. Its analysis is based upon:

- A required SNR of 19dB to allow the DTT receiver to decode 256-QAM DVB-T2 broadcast signal with a transmission rate of 40Mb/s per DTT channel.
- The DTT receiver is at the edge of coverage (minimum DTT signal power), with an interference to thermal noise ratio of -10dB and -6dB (like the UK submission).
- The paper derives that these correspond to Protection Ratios of -57.2dB or -53.07dB and notes that these are considered to be low according to ITU-R BT.2033 Table 6.

The GSMA document [14] is critical of the UK input document based on the following:

- The UE is assumed to be transmitting at full power, with the worst possible coupling loss to a DTT receiver at the edge of DTT coverage.
- The GSMA notes that the 700MHz bandplan limits would apply to all UEs in the UK / Europe, whereas the above conditions can only occur to a small number of DVB receivers that are subject to interference at the edge of their transmitter capability and only in the geographical areas where channel 48 is used.
- The GSMA analysis notes that the UK analysis is based upon C/I considerations (not C/(I+N)) and that output based upon simple C/I considerations are intended to be a threshold for investigation – not to set a limit.
- The GSMA claims that the ACLR value derived by the UK is based upon a high value of DTT ACS (80dB) which makes the ACLR value difficult for a UE to achieve.
- Lastly the GSMA call for a probabilistic Monte Carlo analysis rather than setting limits based upon worst case minimum coupling loss analysis.

The GSMA document [15] discussing preferred frequency arrangements in Region 1 advocates maintaining consistency with the APT lower duplex (i.e. use 2x30MHz, with the lower band starting at 703MHz). They claim that this will provide a global band for roaming with economies of scale. In a separate document [19], Nokia make identical claims and further notes that industry is proposing further studies to verify the adequacy of the protection limit of -26.2 dBm/6MHz advocated by APT.

Vodafone submitted an input to CEPT WPD [20] which reasoned that in the 700MHz band the most likely maximum channel bandwidth is 10MHz. By interpolating the spectrum emission mask limits from tables 6.6.2.1 and 6.6.3 from TS36.101, Vodafone noted that this results in approximately 4.4dBm/MHz less OOB emissions into channel 48 (assuming a 9MHz gap) than using a 15MHz channel bandwidth. They therefore note that OOB emissions will be less in practice than the value derived by applying a filter response to the raw specification spectrum emission mask limits.

2.3 Review of 3GPP specifications

3GPP [21] TS 36.101 Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception [22] – this specification defines the UE device radio performance requirements. Band 28 has been incorporated into Release 11 and 12 of the 3GPP specifications. Table 6.6.3.2-1 of this specification sets the OOB limits that band 28 (ie APT 700 MHz band) can transmit into the frequency range 662-694MHz is -26.2dBm/6MHz. This value is identical to the limit derived by APT to protect their DTT (-34dBm/MHz = -26.2dBm/6MHz).

E-UTRA Band	Spurious emission						
	Protected band	Frequency range (MHz)			Maximum Level (dBm)	MBW (MHz)	Note
28	E-UTRA Band 2, 3, 5, 7, 8, 18, 19, 25, 26, 27, 31, 34, 38, 41	F_{DL_low}	-	F_{DL_high}	-50	1	
	E-UTRA Band 1, 4, 10, 22, 42, 43	F_{DL_low}	-	F_{DL_high}	-50	1	2
	E-UTRA Band 11, 21	F_{DL_low}	-	F_{DL_high}	-50	1	19, 24
	E-UTRA Band 1	F_{DL_low}	-	F_{DL_high}	-50	1	19, 25
	Frequency range	758	-	773	-32	1	15
	Frequency range	773	-	803	-50	1	
	Frequency range	662	-	694	-26.2	6	15
	Frequency range	1884.5	-	1915.7	-41	0.3	8, 19
	Frequency range	1839.9	-	1879.9	-50	1	

Table 1: Band 28 extract selected values from Table 6.6.3.2-1 of 3GPP TS36.101 Release 12

NOTE 15: These requirements also apply for the frequency ranges that are less than FOOB (MHz) in Table 6.6.3.1-1 and Table 6.6.3.1A-1 from the edge of the channel bandwidth.

These tests are part of a suite of tests typically performed by Handset Manufacturers to prepare inputs for certification and by Mobile Network Operators before devices are approved for use on their networks. The tests can be performed by an automated conformance test system such as the TS8980 conformance test system from Rohde and Schwarz.

In addition the tests may be executed by or approved by certification bodies. These include independent certification bodies offering a variety of certification services and the Global Certification Forum (GCF) http://www.globalcertificationforum.org/ . The GCF certification scheme is recognized globally as the de facto standard for certifying all kinds of mobile terminals designed for operation in 3GPP standards such as GSM/EDGE, WCDMA/HSPA and LTE.

A different part of Table 6.6.3.2-1 of 3GPP TS36.101 identifies appropriate limits for the maximum OOB limits allowable from band 20 (800MHz band). These limit the OOB emissions from UE into the duplex downlink band (791-821MHz) to be -50dBm/MHz. The UL and DL bands have a duplex gap of only 11MHz. Hence the band 20 specifications require OOB limits of -50dBm/MHz with a separation of 11MHz, but the band 28 specifications seek to limit to -34dBm/MHz with a gap of 9MHz.

With 3GPP specifications (TS36.101) the spurious emissions limit normally applies from a frequency offset (FOOB) from the TX carrier. Closer to the carrier the permitted emissions are defined by the Spectral Emissions Mask (section 6.6.2.1) and the Adjacent Channel Leakage Ratio (section 6.6.2.3.1). In the band 28 case these requirements also apply to frequencies that are less than FOOB. (Table 6.6.3.2-1: Note 15).

An innovation in the 3GPP specifications to facilitate co-existence is the ability for different cells of a network to transmit control information that controls the maximum power that UEs should use. This can be used to reduce UE power in selected parts of a mobile network where the base stations transmit network signalled value NS-18. When network signalled value "NS_18" is indicated within a cell to a UE operating in band 28, the TX power can be reduced (so called, Additional Maximum Power Reduction A-MPR) by up to 4dB in order to meet the emission limit. This has been inserted in the specifications after analysis [23] to determine how to achieve the APT 700MHz bandplan limits of -26.2dBm/6MHz in the frequency range 692-698MHz. The study in TR 36.820 also concluded that no A-MPR was necessary to meet the required emission levels in the DTT bands up to 694MHz.

If A-MPR was to be used to assist with meeting the UK emissions limits then in some cases it could result in a reduction of up to 6dB in the UE max TX power as currently described in TS 36.101 Release 12.

Firstly there is a Maximum Power Reduction (MPR) level permitted in certain higher order modulation and transmit bandwidth configurations. This can be up to 2 dB as shown in the following table.

Modulation	Channel bandwidth / Transmission bandwidth (N_{RB})						MPR (dB)
	1.4 MHz	3.0 MHz	5 MHz	10 MHz	15 MHz	20 MHz	
QPSK	> 5	> 4	> 8	> 12	> 16	> 18	≤ 1
16 QAM	≤ 5	≤ 4	≤ 8	≤ 12	≤ 16	≤ 18	≤ 1
16 QAM	> 5	> 4	> 8	> 12	> 16	> 18	≤ 2

Table 2: MPR Limits extracted from TS 36.101 V12. Table 6.2.3-1: Maximum Power Reduction (MPR) for Power Class 1 and 3

In addition to the MPR, the A-MPR adds further power reduction in certain cases. The case of Network Signalling Value 18 and band 28 is presented below.

Network Signalling value	Requirements (subclause)	E-UTRA Band	Channel bandwidth (MHz)	Resources Blocks (N_{RB})	A-MPR (dB)
NS_18	6.6.3.3.11	28	5	≥ 2	≤ 1
			10, 15, 20	≥ 1	≤ 4

Table 3: A-MPR limits for NS_18 and Band 28 extracted from TS 36.101 V12. Table 6.2.4-1: Additional Maximum Power Reduction (A-MPR)

MPR and A-MPR power reductions may be combined giving up to 6dB total power reduction in certain cases.

A-MPR could be considered as part of the solution to achieving low emissions in the DTT band. This would result in lower LTE UE TX power in regions where CH48 is used. This lower power would most likely only apply to the lower 10MHz channel in the 700 MHz band. The trade-off is adopting this feature in a network would be the impact to the maximum achievable throughput in locations where channel 48 is used because the maximum power available in the uplink would no longer be permitted which would likely reduce the maximum range a mobile could be from the base station.

2.4 Overview of technical inputs to CEPT for 700 MHz channel plan configurations

The importance of protecting DTT channel 48 within Europe has led to the establishment of a technical committee within CEPT PTD to examine the simulations, models, parameters and studies for the protection of DTT services. The CPG PTD met in Ljubljana in September 2013 at which a number of technical reports were submitted for consideration of the OOB measurement limits into DTT, simulation parameters including Monte Carlo analysis and methodologies. We list below a number of the relevant papers that were submitted:

- Clarification on OOBE measurement results – Nokia/Nokia Institute of Technology [24]
- Summary results of Monte Carlo Simulations by EBU – EBU [25]
- AI 1.2 – Level of LTE OOB for different number of user –IRT [26]
- Modelling of adjacent band compatibility between IMT and DTT – GMSA [27]
- Simulation results on the DTT interference probability_INdT – Nokia Institute of Technology [28]
- IMT OOBE_France – France [29]
- Compatibility Calculation methods – Broadcast Network Europe [30]
- MB_Assessment of MS UE interference into BS receivers – Media Broadcast GmbH [31]

The general overview of these inputs reveals clear differences between the broadcast community and the mobile community based on differences in view of:

- Resulting OOBE limits
- Use of Monte Carlo analysis, methodology and set up
- System simulation parameters

The debate regarding the resulting OOBE limits shows a difference between the view from the mobile community which suggests (Nokia) that the specification is met plus a small margin of -8 dB for a 20 MHz LTE channel BW is needed.

There is some agreement in the proposed additional attenuation for multiple UEs sharing a 10 MHz bandwidth between the Nokia paper and the French paper which both suggest a maximum 19 dB attenuation for more than 2 UEs sharing in a 10 MHz BW. However, the paper from IRT found variation in the ACLR from four different terminal types and the aggregate ACLR did not correlate with the number of terminals of a given terminal type. They suggest that since the ACLR is so variable only the minimum specification level can be assumed.

Much of the disagreement is based on the proper use of Monte Carlo simulation: EBU and BNE note that both the location and time of the interference from a UE continually changes. Their papers suggest that the time element and probability of interference occurring should be included in the compatibility calculations. The GSMA Monte Carlo analysis uses a random distribution of UEs and calculates the probability of interference without consideration of the time domain.

Some of the papers present results from measurements and others from simulations. The Nokia paper, the GSMA, the French paper provide results from simulations and the IRT paper present results from measurements. Other papers such as that from Media Broadcast provide an overview of the parameters used for simulations and argue that UE power control poses a worse source of interference with UEs without power control and therefore that Transmit Power Control needs to be taken into consideration when conducting simulations. The input papers clearly represent the vested interests of different parties who can be identified with the broadcasting sector or the mobile sector. For the purposes of our study we use the limits derived from the minimum coupling loss approach submitted by the UK and seek to determine the feasibility of achieving this limit. Whilst it is likely the mobile industry could argue that this is too stringent and the broadcasters it does not include certain interference effects this study investigates the feasibility of achieving the MCL limit through technology development of the RF front end. If this MCL limit (derived for a UE in boresight of a DTT receive antenna at full power with the most sensitive DTT modulation scheme and small noise rise) can be achieved then it is likely that the incumbent DTT services will be able to be confident that any award of spectrum for mobile use will not degrade the provision of their services.

2.5 Summary of the different OOB limits

The derived values based upon the analysis performed for APT, CEPT and 3GPP differ widely. These values are summarised in Table 4.

Source	dBm (6 or 8 MHz)	dBm/MHz
UK/CEPT OOB value 1 (I/N = -6dB)	-52.6 (8 MHz)	-61.6
UK/CEPT OOB (I/N = -10dB)	-58.6 (8 MHz)	-67.6
3GPP OOB B28	-26.2 (6 MHz)	-34.0
CEPT 030 (800 MHz)	-65 (8 MHz)	-74.0
APT Rep 24 OOB	-26.2 (6 MHz)	-34.0

Table 4: UE OOB limits defined by the different bodies for different 700MHz bandplans

These values differ markedly and the key reasons for any differences are the following:

- Different set of technical parameter values used such as UE power, ACS, band gap, etc., as well as different equipment setup and coexistence environment
- Different choice of coexistence analysis; Monte Carlo vs. Minimum Coupling Loss.
- The most conservative limits are based upon impacting a user at the edge of DTT coverage by the lowest amount permissible (10dB below noise floor) whilst subject to a UE transmitting at full power directly into the TV antenna (boresight at worst possible distance).
- The least conservative limits are based upon a judgement after a wide range of assessments based upon the performance impact of DTT standards that are likely to be more robust that those likely to be deployed in the UK beyond 2018 (where DVB-T2 is likely to be used).

The choice of the level of protection to use requires careful judgement. No radio system is planned on the basis of providing 100% service availability – though a higher level of system availability is expected for some technologies (DTT) than others (mobile communications). Setting a more relaxed level of interference into DTT receivers will increase the likelihood of users in some areas being subject to increased interference. Early indications are that the limits used in the APT band are achievable (but not easily so) in practice. The practicality of being able to improve on the APT limits by approximately 30dB is assessed in this study.

2.6 Possible duplex configurations in the 700 MHz band

This section presents the possible duplex configurations that could be implemented in the 700 MHz band. In section 3.1 we describe in detail the technical elements of the RF front end architecture of a handset which is important to understand when considering the different duplex configurations.

There are a number of possible duplex configurations for the 700 MHz band plan options to establish the available channel raster. For example, in the 2x30 MHz band plan three 2 x 10 MHz channels could be assigned to operators using an 18 MHz duplex gap. In this section we identify the duplex configurations that may be possible in the proposed band plans.

In order to be able to allocate a 20MHz channel anywhere in the band, a 20MHz overlap must exist between the 2 filters of a dual duplexer. If it can be assumed that spectrum will be auctioned in blocks of 5 MHz on a 5MHz raster from the start of the band (703 MHz), then the overlap between the 2 filters can be reduced to 15MHz. This is the approach adopted in the APAC700 B28 case and is described in section 8.1.1 of 3GPP TR 36.820 [23].

To avoid restrictions in 20MHz channel usage Region 1 band-plans which require dual duplexer implementations, one of the following requirements must be met;

1. The overlap between filters must be 20MHz
2. 20MHz channels must be placed on a 5MHz raster from the start of the band and a 15MHz overlap can be used.

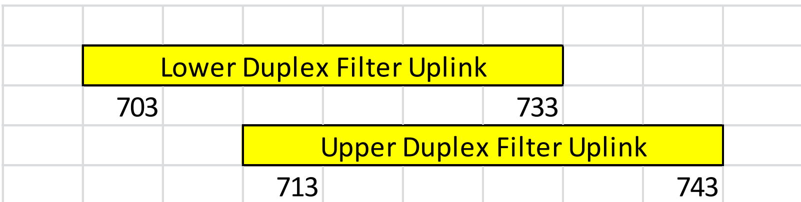

Figure 2: Example Option 4 Dual Duplexer Frequency Assignments Uplink

Figure 2 shows example configuration for Options 4 with a dual duplexer frequency assignment uplink.

All possibilities of meeting the 5MHz raster and 15MHz overlap together with 20MHz overlap cases, using equal bandwidth upper and lower duplexer filters, are tabulated below.

Implementation No.	Lower filter only (MHz)	Overlap (MHz)	Upper filter only (MHz)	Lower filter BW (MHz)	Upper filter BW (MHz)	Band BW (MHz)	Comments
1	5	15	5	20	20	25	Single filter solution possible
2	10	15	10	25	25	35	Possible overlap assignment for 35 MHz option 2
3	15	15	15	30	30	45	APT700 band 28 case
4	5	20	5	25	25	30	Single filter solution possible
5	10	20	10	30	30	40	Possible overlap assignment for 40 MHz option 4, 5 and 6

Table 5: Dual Duplexer Filter overlap possibilities

We have also investigated cases where different bandwidths could be used for upper and lower filters. We refer to these as Asymmetric Dual Duplexers. In principle the narrower bandwidth filters could be used in either the upper or lower duplexer positions. We have chosen to position the narrower filter in the lower duplex position as we anticipate that this is where it would be most beneficial. Asymmetric dual duplexer implementations have 2 potential advantages. In the 40MHz Band cases, they enable a narrower BW filter to be used in the lower duplex position. This may make it easier to achieve more attenuation in the DTT band than could be achievable with a 30MHz filter. The second minor advantage is that in 35MHz band cases, the restrictions on the location of 20MHz carriers to a 5MHz raster from the band start could be lifted. Table 6 below shows the asymmetric filter possibilities.

Implementation No.	Lower filter only (MHz)	Overlap (MHz)	Upper filter only (MHz)	Lower filter BW (MHz)	Upper filter BW (MHz)	Band BW (MHz)	Comments
6	10	15	15	25	30	40	Possible overlap assignment for 40 MHz option 4, 5 and 6
7	5	20	10	25	30	35	Possible overlap assignment for 35 MHz option 2
8	5	20	15	25	35	40	Upper filter BW too large

Table 6: Asymmetric Filter Possibilities

Each of the Dual Duplexer bandwidth and overlap combinations is labelled with an Implementation No. We can now combine these with the band options to calculate the pass-band corner frequencies for dual duplexer implementations of the 35MHz bandwidth Option 2 and the 40MHz bandwidth Options 4, 5 and 6. We note that there is 1 symmetric and 1 asymmetric implementation possibility for each band option. The following tables identify the possible implementations for each option.

Option 2		Uplink Passband (MHz)		Downlink Passband (MHz)		comments
Full band		698	733	753	788	
Implementation 2	Lower filters	698	723	753	778	25 MHz filter
	Upper filters	708	733	763	788	25 MHz filter
Implementation 7	Lower filters	698	723	753	788	Narrower 25 MHz filter but only 4 MHz transition bandwidth
	Upper filters	703	733	758	788	Same 30 MHz filters as APT700 band 28 lower duplex

Table 7: Option 2 Dual Duplexer Implementation Possibilities

Option 4		Uplink Passband (MHz)		Downlink Passband (MHz)		comments
Full band		703	743	751	791	
Implementation 5	Lower filters	703	733	751	781	30 MHz filter
	Upper filters	713	743	761	791	30 MHz filter
Implementation 6	Lower filters	703	728	751	776	25 MHz filter
	Upper filters	713	743	761	791	30 MHz filter

Table 8: Option 4 Dual Duplexer Implementation Possibilities

Option 5		Uplink Passband (MHz)		Downlink Passband (MHz)		comments
Full band		701	741	751	791	
Implementation 5	Lower filters	701	731	751	781	30 MHz filter
	Upper filters	711	741	761	791	30 MHz filter
Implementation 6	Lower filters	701	726	751	776	25 MHz filter
	Upper filters	711	741	761	791	30 MHz filter

Table 9: Option 5 Dual Duplexer Implementation Possibilities

Option 6		Uplink Passband (MHz)		Downlink Passband (MHz)		comments
Full band		703	743	748	788	
Implementation 5	Lower filters	703	733	748	778	30 MHz filter (UL same as band 29=8 lower duplex UL)
	Upper filters	713	743	758	788	30 MHz filter (DL same as band 28 lower duplex DL)
Implementation 6	Lower filters	703	728	748	773	25 MHz filter
	Upper filters	713	743	758	788	30 MHz filter

Table 10: Option 6 Dual Duplexer Implementation Possibilities

We have considered example operator frequency assignments for the 2 implementations of the Option 4 bandplan which includes one implementation of 2 x 30 MHz (symmetric) and one implementation of 1 x 30 MHz and 1 x 25 MHz (asymmetric). In both cases, we show in the following figures the assignment of 10MHz each to 4 operators, 20MHz each to 2 operators and 2 x 10 MHz assignment plus 1 x 20MHz which is located at the band centre.

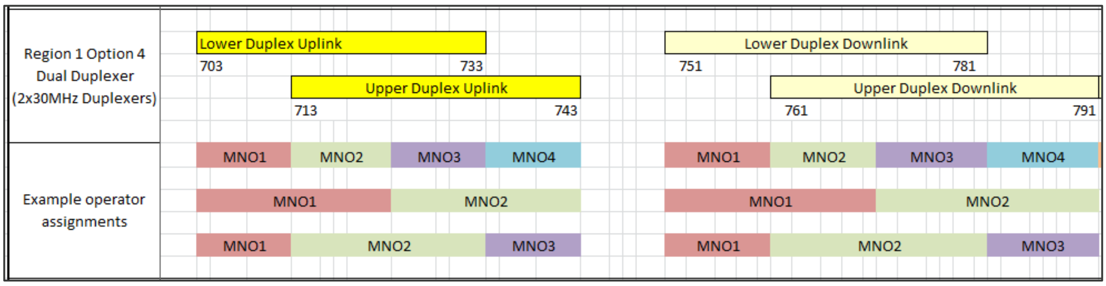

Figure 3: Region 1 Option 4 2x30MHz Duplexers, -Example Operator assignments

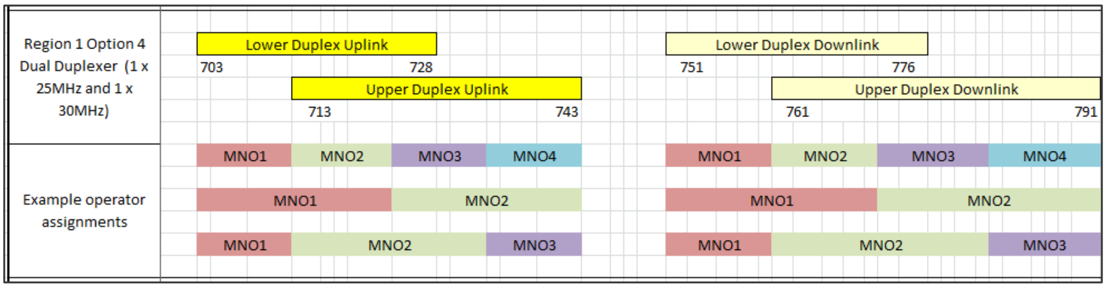

Figure 4: Region 1 Option 4 1x30MHz & 1x25MHz Duplexer, -Example Operator assignments

The configurations demonstrate the possible channel assignments that could be made from the implementation of Option 4, the most spectrally efficient case being four operators with 2 x 10 MHz each.

2.7 Final bandplan options for consideration

The out of band emissions analysis has revealed that to achieve a certain rejection in the adjacent band to protect DTT a minimum separation distance (transition bandwidth) is required. This is to establish the extent of the likely stop band the filter manufacturers can expect to design to when considering a European band plan.

Therefore, we propose a final set of bandplan options that includes an additional option 6 for consideration throughout the study. Figure 5 shows a chart of the final band plan options which include option 1, 2, 4, 5 and 6.

Option 6 is a newly suggested option which covers a 2 x 40 MHz bandwidth with a much narrower duplex gap in between the upper and lower bands. This option was devised in addition to the others on the basis filter manufacturers could support this type of configuration.

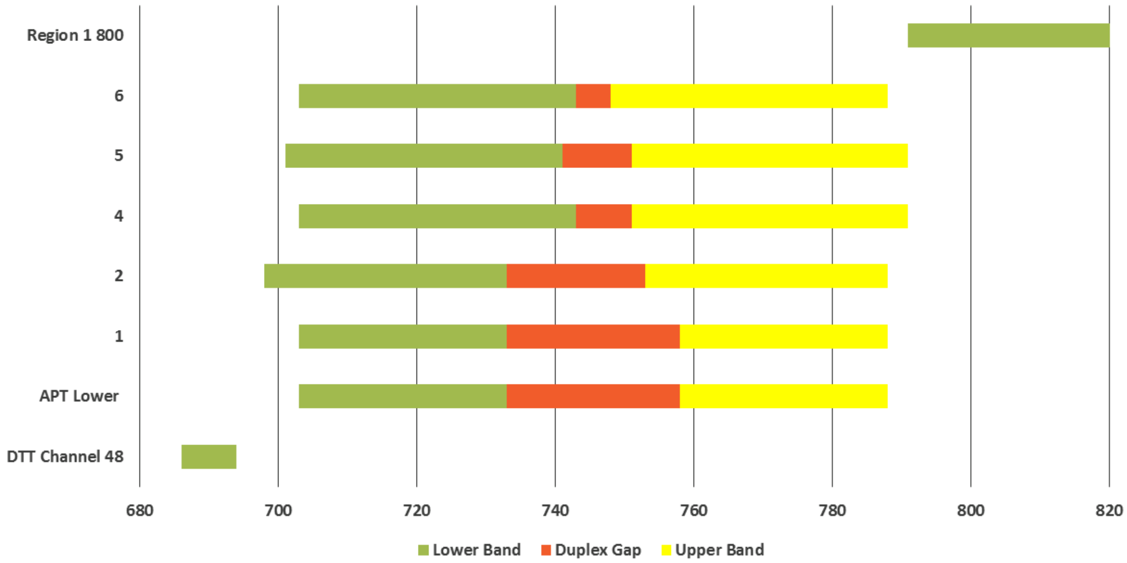

Figure 5: Final set of band plan options considering the stop band limitation

3. Technical Filter Analysis

In this chapter we discuss the technical characteristics and the performance of the filter technologies and the UE RF receiver front end architecture. The UE and RF front end design are critical for the development of handsets and choice of particular bands from a vendor's perspective.

In the LTE standard there are now over 40 different frequency bands to choose from each with its own set of emission limits, technical features and characteristics, many of which are common across the frequency bands. However, in some cases new frequency bands have been proposed due to regional and sometimes national variations due regulatory requirements which have meant an increase to the number of standard bands.

This wide choice of frequency bands presents a commercial challenge to handset vendors who must decide which combination of bands it will adopt and which markets it will adopt. We discuss later in chapter 4 the size of the addressable market for handsets which incorporate the APT700 band and the potential for an EU variant of 700 MHz.

In terms of the impact to the filter design the following sections capture the technical details of:

- RF front end architecture
- Performance
- Constraints
- Cost

We have evaluated the impact across these criteria to determine whether support of dual duplexers in a European variant of the 700 MHz band is practical and cost effective to implement. In addition, we determine whether the European OOB emission limits can be achieved using current technology, or whether further development in UE filter technology is required to support these limits.

3.1 UE RF Front end architecture and enabling technologies

Current UEs support 4 GSM bands and typically 5 WCDMA bands. LTE is also supported by up to 13 bands in the latest Apple iPhone 5S [32]. Additionally UEs support other LTE only bands. These are normally supported on regional variants of UE to minimise cost. Bands have been grouped into low bands sub 1GHz and high bands above 1 GHz however there is a recent trend to split the high band into a high and mid band parts as summarised in the following table. The table shows which bands are supported by each of the standards in use today for those bands that are actually supported in commercial handsets.

	Bands Vs Standards			
	2.5G	3G	4G	
	GSM/EDGE	WCDMA	FDD-LTE	TDD-LTE
High Bands				B42 (3500)
				B43 (3700)
				B38/41 (2600)
				B40 (2300)
			B7(2600)	
Mid Bands		B1 (2100)		
	B2 (PCS1900)			
	B3 (DCS1800)			
		B4 (AWS 1700/2100)		
			B25(1850)	
				B39 (1900)
Low Bands	B5 (GSM850)			
	B8(EGSM/UMTS900)			
			B20(800)	
			B12/17 (700)	
			B13 (700)	
			B14 (700)	
			B28(APT700)	
			B29 -DL (700)	
			Reg_1 (700)	
				B44(APT700)

Figure 6: Mobile Communications bands vs. Standards

Reg_1 (700) in the table refers to the new ITU Region 1 700MHz band. The breakdown of LTE band usage in 194 commercially deployed networks as at August 2013 is as outlined in the next figure from GSA [33].

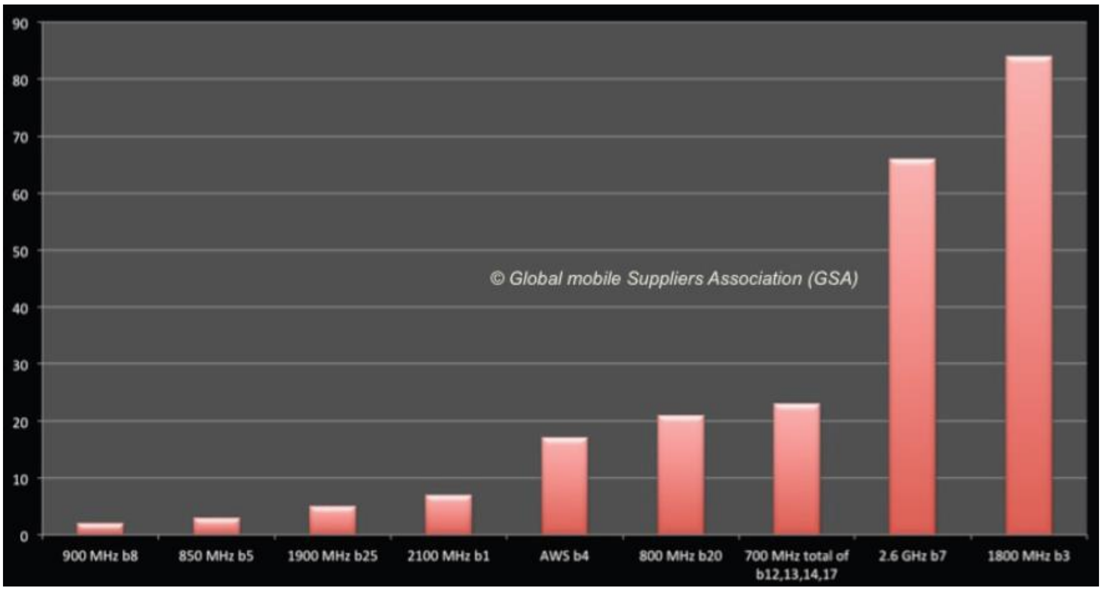

Figure 7: LTE deployed networks vs frequency band

This figure indicates the current priority LTE bands to be supported by UEs. Different LTE band sets are supported by various regional variants of the UE. An example of the iPhone5, with 3 regional variants follows. Models A1428(GSM) and A1429(CDMA) are supplied in North America. ModelA1429(GSM) is supplied into Asia-Pacific and European markets. Other manufacturers, for example Samsung, have significantly more regional UE variants.

Model A1428 (GSM model)	Model A1429 (CDMA model)	Model A1429 (GSM model)
2 (1900 MHz)	1 (2100 MHz)	1 (2100 MHz)
4 (AWS)	3 (1800 MHz)	3 (1800 MHz)
5 (850 MHz)	5 (850 MHz)	5 (850 MHz)
17 (700b MHz)	13 (700c MHz)	
	25 (1900 MHz)	

Table 11: iPhone5 LTE band support

A representative block diagram of a current high end UE follows. Two antenna paths are used to support downlink 2x2 MIMO. In current LTE implementations, one uplink (UL) transmit (TX) path is used in an Uplink Multi-User MIMO configuration. Later releases introduce Uplink MIMO with 2, 4 and 8 streams. Support for 2x2 UL MIMO is not shown in the diagram and will become more prevalent over the coming years as shown in [34]. However, UL MIMO may start to be incorporated into tablets before smartphones due to the difference in form factor size. Signals are routed from a highly integrated transceiver device via filters or duplexers to the antennas by switches. Power monitoring and antenna tuning functions are incorporated.

Intra-band Uplink Carrier Aggregation is also included in the standard and is in development with UE manufacturers. Intra-band UL CA requires the supported TX high and low band PAs to be on simultaneously. This places a higher linearity requirement on the switches as a harmonic or intermodulation product of the uplink signals may fall in a receive band and desensitise or block the receiver.

Note that in addition to the cellular receivers care must be taken that Wi-Fi, Bluetooth and GPS receivers are also not adversely impacted by IM products.

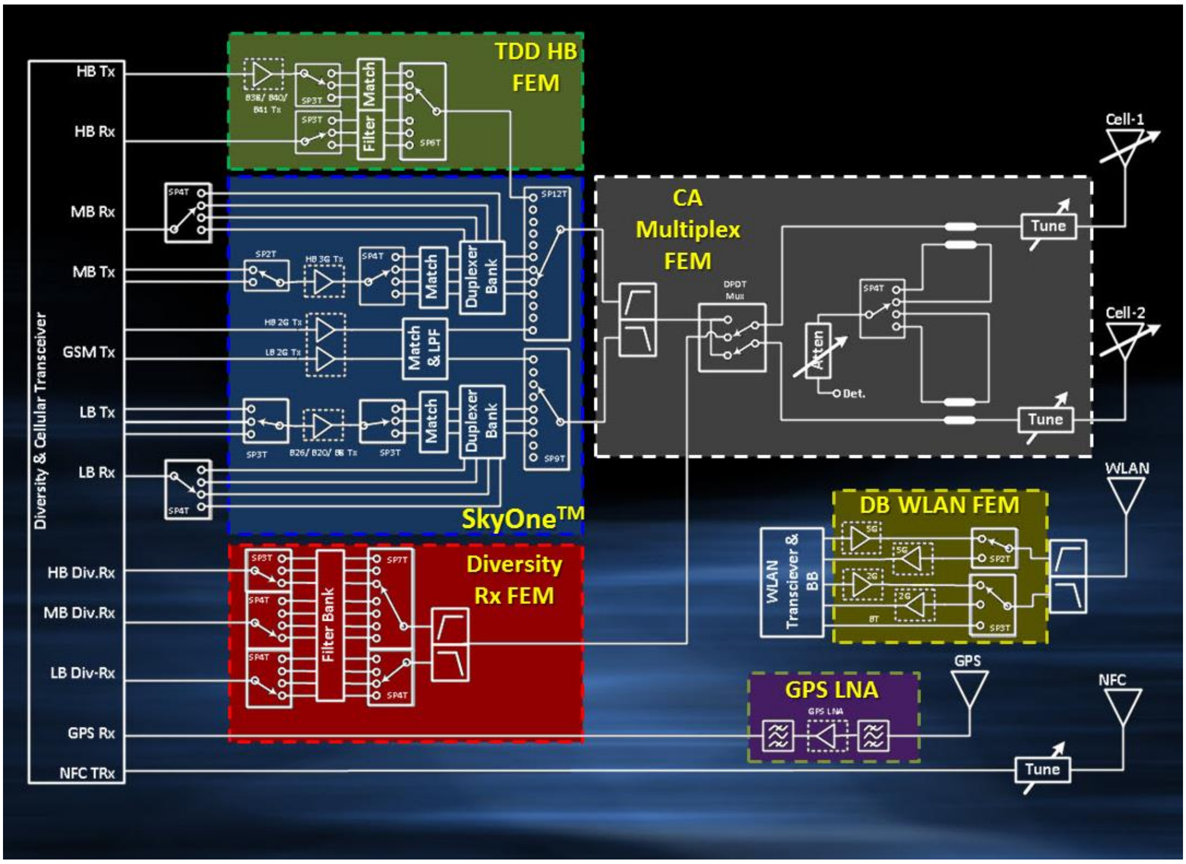

Figure 8: UE High Level Block Diagram (SkyWorks [35])

Figure 8 shows one example of a UE architecture which captures all the possible features expected from the front end module such as diversity, GPS, Bluetooth, Wi-Fi, cellular etc. Other example architectures may include features such as MIMO, mix of more frequency bands and carrier aggregation.

There are currently four variants of the SkyOne device available. These support Quad Band GSM and Penta Band WCDMA and different LTE band combinations. The LTE band combinations contain some global roaming bands and some regional bands as described in Figure 9.

	Skyworks SkyOne published variants and supported bands				Applicable Regions		
					Region 1	Region 2	Region 3
	SKY78010	SKY78011	SKY78015	SKY78021	EU/Africa	Americas	APC
Band 1							
Band 2				Note 1			
Band 3							
Band 4							
Band 5				Note 2			
Band 8							
Band 18				Note 2			
Band 19				Note 2			
Band 20							
Band 25				Note 1			
Band 26				Note 2			
Band 28							
Band 29							
Summary	US	EU/APC	EU/APC	World			

Figure 9: LTE Bands Supported by SkyOne variants.

Note 1: Band 25 is a 5MHz extension of Band 2. Therefore a single Band 25 duplexer will also support Band 2.

Note 2: Band 26 encompasses Bands 5, 18 and 19. Therefore a single Band 26 duplexer will also support Bands 5, 18 and 19.

This figure indicates that the SKY78010 device is intended primarily for US regional support and that the SKY78011 and SKY78015 devices are intended primarily for EU/APC regional support. The SKY78021 supports a total of 8 bands making it suitable for World phone applications.

The SKY78010, SKY78011 and SKY78015 devices each have 3 spare TRX ports which could be used to add external duplexers and amplifiers to support other bands.

In comparison the RF360 highly Front End module from Qualcomm also incorporates a feature to enable band combination customisation. Details of this device are provided by Qualcomm [36] some of which are repeated below. This product integrates more RF Frontend parts, for example Envelope Tracking.

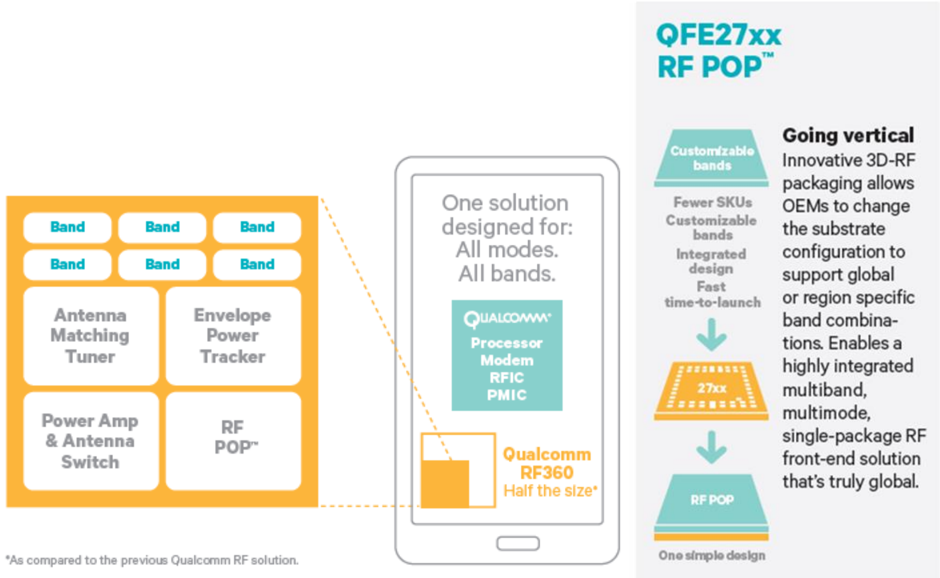

Figure 10: RF360 Functions (Qualcomm) [36]

Physically the device is made up of 2 parts a lower part containing common functions and an upper part which contains band specific parts. These are joined together in a Package on Package (POP) structure.

A more detailed diagram of the POP structure is provided in a Qualcomm webinar published at [36]. This is shown in Figure 11.

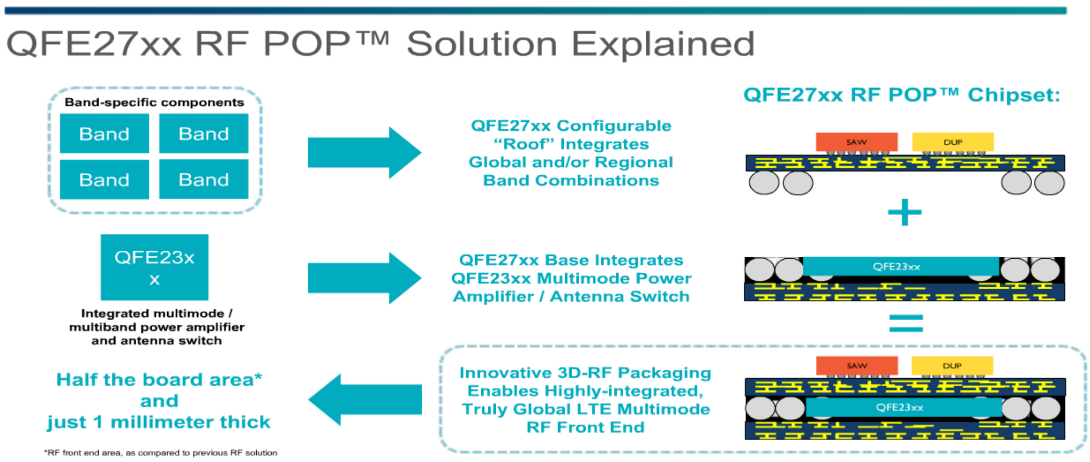

Figure 11: RF360 Package on Package, POP, (Qualcomm)

The top part, referred to as the "Roof" in the preceding figure, of the 2 part construction contains the frequency specific Duplexer and SAW filters. Multiple versions of the Roof part are available to support different band combinations.

It is interesting to note that neither Qualcomm nor Skyworks manufacture SAW or BAW filters.

We examine the Low Band configuration in more detail to assess the impact of the proposed new Region 1 bandplan. In the following diagram we consider the low band part of one of the antenna paths. Two low-band paths will need to be supported in order to meet the legacy GSM and WCDMA requirements. If all low-band possibilities were to be supported and assuming dual-duplexer implementations for the APT700 band and the Region 1 700MHz band, then 8 new duplexers and 1 bandpass filter would be required. It is not realistic to support all of these bands in UE as the majority of users which would never require use of all bands. This leads to decisions on which bands should be supported and in which combination groups.

In addition to the band options listed, it is likely that another US Low band could emerge from the current FCC 600MHz band study, [37].

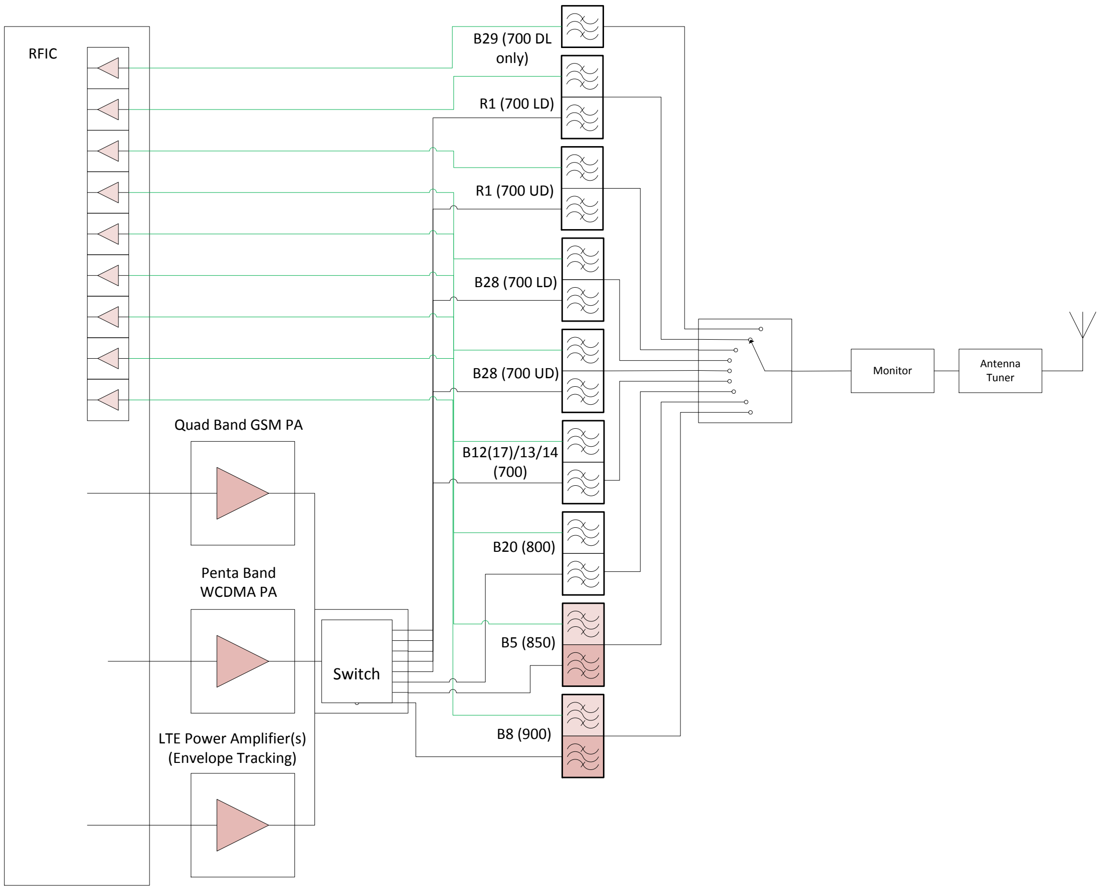

Figure 12: UE RF FE Block Diagram – Low Band Part

The key component parts of the UE RF Front End are;

- RFIC
- Power Amplifiers
- Duplexers
- Switches
- Antenna Tuner
- Antenna

The RFIC is a highly integrated device which implements the TX and RX low power RF and signal processing. Normally they have a number of RF ports which are routed to the receiver duplexer filters. The number of RF ports supported by a device can limit the number of bands that can be supported in a UE.

The remaining parts including PA, Filters and switches are normally integrated in a Front End Module (FEM).

Power Amplifiers range from single band devices through to quad band GSM devices to multiband-multimode devices. The article "CMOS and SOI Invade RF Front End" [38] provides some insights from FEM vendor Triquint into PA choices vs. the number of bands to be supported.

We provide two particularly interesting quotes from Shane Smith, Vice President of mobile devices global marketing at TriQuint from [38] relating to the number of bands currently supported in handsets which we re-present below:

"*A handset that requires four or more bands may need multi-mode, multi-band PAs, while cheaper discrete PAs are suitable for a phone with anything less than that*."

"*Of all the smartphones shipped this year, the average band count is actually still less than four. Some 60% to 70% of the market would probably lean towards a more discrete solution, whether that is a discrete PA or putting two power amps in one package. Some 30% to 40% of the market would take advantage of multi-mode, multi-band PAs. The ones shipping today would probably (support) six to seven bands. Then, on top of that they also have discrete PAs, which can be populated or de-populated depending on the region they want to support*."

One example integrated chip is the Qualcomm RF360 [39] this is a commercially available chip on the market that is marketed as a multi-mode and multi-band RF front end supporting the core LTE frequency range from 700 MHz to 2700 MHz. However, the RF360 is a high-end component and would likely be for a premium device and not a mid-market device. The Samsung Galaxy Note [40] has this chip incorporated.

Another FEM that is less integrated compared to the RF360 is a chip from Skyworks called the SkyOne [41] product which was launched in Autumn 2012 supports multiple bands and technologies in a similar way to the Qualcomm RF360.

The options for RF filter and duplexer implementation are Surface Acoustic Wave (SAW), Bulk Acoustic Wave (BAW) and Film bulk Acoustic Resonator (FBAR). SAW is the lowest cost technology starting from 50 cents US per unit[2] with a temperature compensated variant most applicable in the UE RF Front End (RFFE) case. BAW realisations have lower losses, better power handling capability and better robustness than SAW. However they are more expensive and therefore more likely to be used at higher frequencies, above 2.5GHz, where their advantages over SAW implementation are more pronounced. FBAR filters have higher Q than both SAW and BAW and the advantage of steeper transitions from passband to stop-band but are also more expensive than SAW. On this basis FBAR filters are usually found in applications with higher frequencies typically above 1GHz.

[2] This unit cost assumes unit volumes in the order of 3-5 million and would likely be 10-20% lower for higher unit volumes.

Switches are used to select the active TX and RX signal paths through the RFFE. Insertion loss and linearity are the most important requirements. Linearity has become a critical requirement in UEs implementing inter band CA as there is a risk of harmonics or IM products falling inside an active receiver band and desensitising the receiver.

Antenna implementation can cover all bandwidths with the high band and low band paths combined in a diplexer. Active antenna matching is used to tune antenna in some implementations. Antenna Tuning where aggregated low band and high band carriers are applied to the same antenna is challenging. A possible solution in some cases to apply the tuning on the low frequency side of the Low Band – High Band combining Diplexer only. This can be done because the High Band antenna is normally broadband and will not require tuning. The predominant emissions close to the carrier in a UE uplink path result from intermodulation in the PA and are characterized by Adjacent Channel Leakage Ratio, ACLR.

The UE ACLR specifications are presented in 3GPP TS 36.101 which is the specification for user equipment (UE) radio transmission and reception [22].

There are 2 emissions regions defined, ΔFOOB close to the carrier and the Spurious domain further away as shown in Figure 13 from the specification.

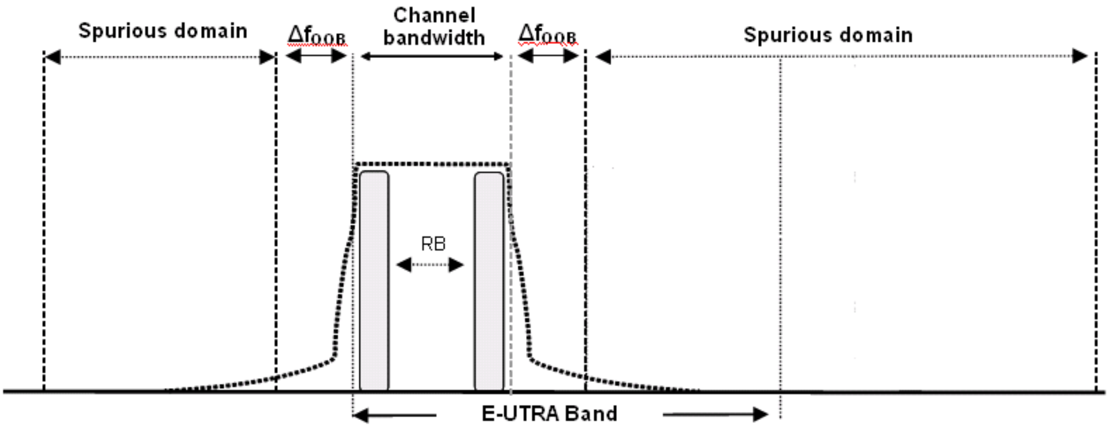

Figure 13: Transmitter RF spectrum

ACLR is specified inside the ΔFOOB region as depicted in the specification Figure 13 and we consider this to be the most appropriate specification to use to estimate emissions in the DTT band.

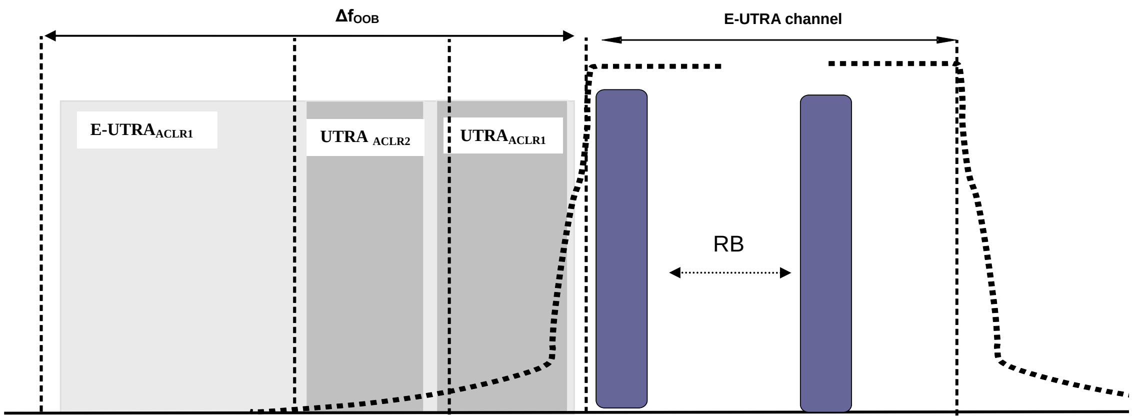

Figure 14: Adjacent Channel Leakage requirements for one E-UTRA carrier

ACLR is specified for both UTRA and E-UTRA. These specifications allow a first estimate of emissions which would fall in DTT CH48. We examine the UTRA and E-UTRA cases separately.

3.2 Filter architecture, design and performance

Three technologies are in use for realisation of mobile device duplexer filters. These are Surface Acoustic Wave (SAW), Bulk Acoustic Wave (BAW) and Film Bulk Acoustic Resonator (FBAR). The SAW and BAW filters are additionally available in temperature compensated versions.

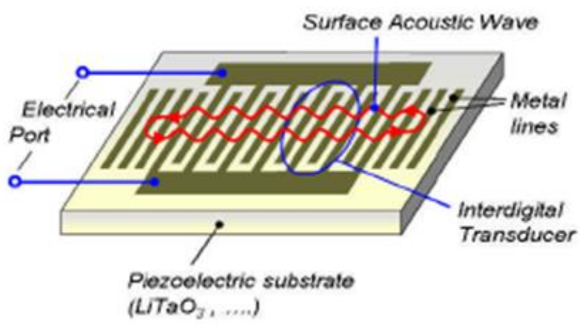

Figure 15: SAW Filter Architecture [42]

SAW filters are the least complex to manufacture and are lowest cost. Their performance can be improved by temperature compensation. A typical SAW filter realisation uses 2 mask layers has a temperature co-efficient of about 40ppm/degC. Temperature compensation requires a further mask layer and a temperature co-efficient of about 20ppm/degC.

Current SAW Filter realisations are limited to fractional bandwidths of the order of about 5%.

BAW filters are available in 2 realisations, Solidly Mounted Resonator (SMR) and Film Bulk Acoustic Resonator (FBAR). Both realisations are more complex and more expensive than SAWs.

In the SMR-BAW case, waves propagate vertically through the material bulk. Significantly more mask layers, typically 14, are necessary for filter realisation. BAWs have higher Q and can implement steeper filter roll-off. Their intrinsic temperature coefficient is equivalent to a TC-SAW at about 20ppm/deg C. They also have good power handling capability.

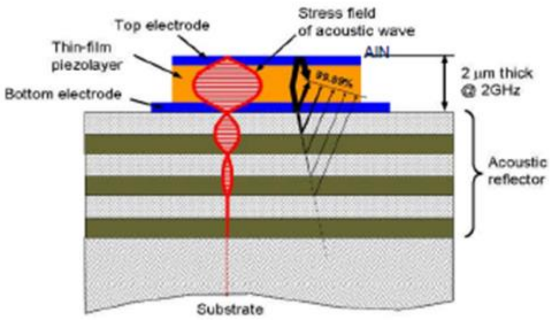

Figure 16: BAW Filter Architecture [42]

FBAR (Film Bulk Acoustic Resonator) filters incorporate acoustic waves travelling in vertical direction as in the SMR-BAW case but have an air cavity below the piezo layer. They have the highest published Q's and can implement steep transitions from pass-band to stop-band. Their temperature co-efficient is about 30ppm/degC.

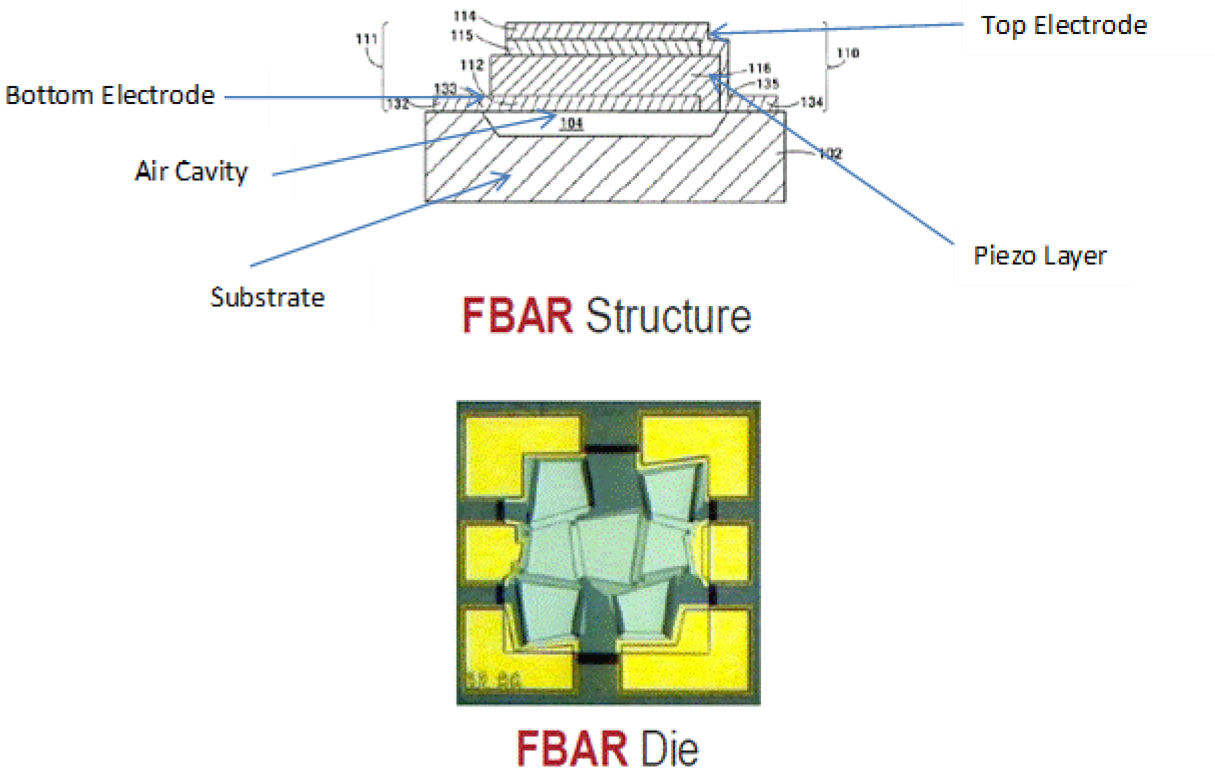

Figure 17: FBAR filter architecture [43]

The highest published Q values for FBAR, SMR-BAW and SAW filters are tabulated below.

Q Values		
BAW	FBAR 2GHz	3700
	FBAR 1GHz	4900
	SMR 2GHz	2600
SAW	1GHz	1300
	2GHz	1500

Table 12: Q values of different filter technologies

Typical use cases for SAW, TC-SAW and BAW filters are presented in Figure 18.

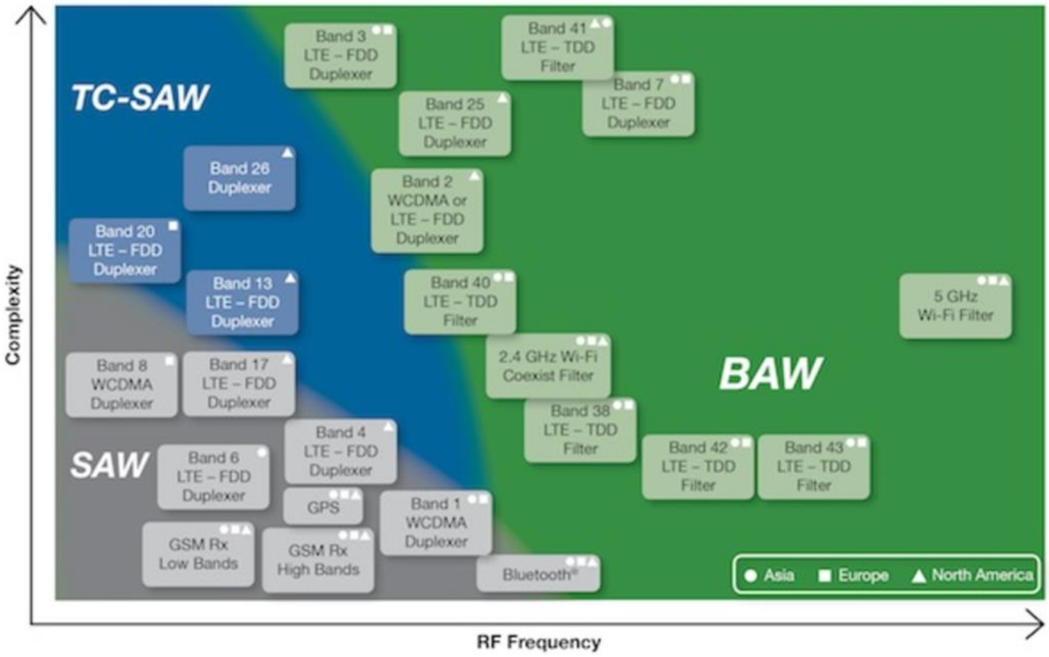

Figure 18: Illustration of filter technology use cases across cellular bands [42]

In the 700MHz band case, the most applicable filter technology is TC-SAW. This is primarily because of its reasonable performance and low cost. In cases where significant technical challenges arise, in particular if steeper transition to the stop-band and good insertion loss is required then FBAR is the most likely next best choice.

Presently FBAR filters are not manufactured for applications which can be served by SAW technology as the price difference is too great. Multiple filters can be incorporated in the same package reducing space. Additionally the Antenna port is combined eliminating the need for an external switch. Examples are Avago's FBAR Quadplexer and Quintiplexer designs which incorporate and combine multiple filters within the same package.

Duplexer Filters may also be assembled in groups or banks. A duplexer filter bank is shown in the SkyOne block diagram from Skyworks, Figure 8.

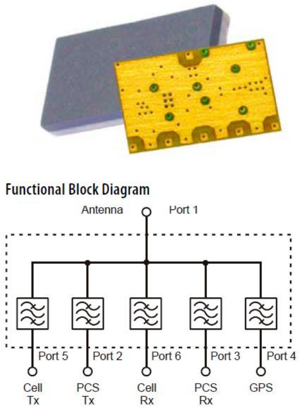

Figure 19: Functional block diagram of a multiplexer filter

Current power amplifier architectures usually have a Quad Band PA Module, a Penta band WCDMA PA module and several LTE PA Modules. The present trend is towards Multi-mode, Multi-Band PA devices. This will most likely be implemented as 3 PA modules covering a Low, Mid and High grouping of bands. Envelope Tracking will be required to optimise the Multi-mode Multi-band PA efficiency.

The choice of filter implementation ultimately comes down to a number of decisions to be made by the vendor in terms of the addressable, the cost of serving that market, impact on performance etc.

The filters examined above illustrate the technical characteristics in each case and we summarise in the table below impact against each criteria.

Filter type	Insertion loss (Typical)	Fractional bandwidth	Q	Cost (Duplexer)
SAW	2 - 15 dB	0.1% - 40%	1300 @1GHz	Low performance spec High Performance spec
BAW	1-3dB	3%	2600@2GHz	>high performance spec SAW
FBAR	2-3.5dB	14%	4900@1GHz	>high performance spec SAW

Table 13: Typical performance of filter technologies

3.3 Estimation of emission methods into DTT band

The following section examines a number of different methods of estimating emissions into the DTT bands which include:

1. UTRA (ACLR 1 & ACLR 2)
2. E-UTRA 10 MHz (ACLR)
3. E-UTRA 20 MHz (ACLR)
4. Power amplifier data sheet
5. 18 MHz offset ACLR figures from [18]
6. ITU-R BT 2215-3 document [18]

This study is focussed on LTE technology which is likely to be deployed in the 700 MHz band, however, we examine the ACLR adopted in 3G handsets to understand what can be achieved by a significant handset base operating in the 3G bands.

3.3.1 UTRA Case

ACLR is specified for the adjacent (ACLR1) and next adjacent (ACLR2) 5MHz channel blocks. The ACLR is measured in a 3.84MHz BW centred in each of these blocks. The specification TS 36.101 Table 6.6.2.3.2-1: Requirements for UTRA ACLR1/2 gives the following limits;

ACLR1	**ACLR2**
33dBc	36dBc

Table 14: Adjacent channel limits UTRA case

When the bottom corner frequency of a 20MHz E-UTRA carrier is located at 703MHz, the ACLR2 region is very close to the CH48 top frequency of 694MHz. A further 5MHz block away would fall inside CH48. We would expect the ACLR in such a block to be about 3dB lower than ACLR2. Therefore we can estimate the emissions inside CH48 as follows;

$$E_{CH48} = 23\text{dBm} - 36\text{dBc} - 3\text{dB} - 10.log10(3.84) = -21.84\text{dBm/MHz}$$

3.3.2 E-UTRA Case

The E-UTRA ACLR1 is specified for a 20MHz block adjacent to the 20MHz E-UTRA carrier. The specification limit is 30dBc and the measurement BW is 18MHz. We make another estimate of the emissions in CH48 below.

$$E_{CH48} = 23\text{dBm} - 30\text{dBc} - 10.log10(18) = -19.55\text{dBm/MHz}$$

The E-UTRA ACLR1 is specified for a 10MHz block adjacent to the 10MHz E-UTRA carrier. The specification limit is 30dBc and the measurement BW is 9MHz. This gives another estimate of the emissions in CH48.

$$E_{CH48} = 23\text{dBm} - 30\text{dBc} - 10.log10(9) = -16.54\text{dBm/MHz}$$

These figures can be considered as upper limits as in practice the UE would have some margin against the specification. Additionally we would expect the ACLR/MHz to drop off with increasing frequency offset from the carrier corner frequency at 703MHz.

3.3.3 Power Amplifier performance

Power amplifiers are used to estimate how much ACLR in band and taking the worst case which is E-UTRA ACLR is 3 dB better than the specification.

We have examined a representative PA, the ACPM-5017 from Avago. This device is identified as appropriate for APAC700 applications. The ACLR performance is repeated below.

Electrical Characteristics

– Conditions: Vcc = 3.4 V, Ven = 2.6 V, Ta = 25° C, Zin/Zout = 50 ohm

Characteristics		Condition	Min.	Typ.	Max.	Unit
LTE Adjacent Channel Leakage Ratio	$\text{E-UTRA}_{\text{ACLR}}$	Pout < (maximum power –MPR)		-36	-33	dBc
	$\text{UTRA}_{\text{ACLR1}}$	Pout < (maximum power –MPR)		-39	-36	dBc
	$\text{UTRA}_{\text{ACLR2}}$	Pout < (maximum power –MPR)		-41	-38	dBc

Table 15: Characteristics of power amplifier performance extracted from Avago data sheet [44]

Note the datasheet states that the MPR = 0 for these performance figures.

The worst case performance figures are 2-3dB better than the specification.

Taking the ACLR Specification and the PA performance example we can estimate that an upper limit of the wideband noise level, before TX filtering, falling in Channel 48 will be about -20dBm/MHz.

3.3.4 Measured UE ACLR

The document Measurements of DVB-T2 receiver protection ratio and overload threshold under LTE UE interference in adjacent/non-adjacent channels which is embedded in Report ITU-R BT.2215-3, Measurements of protection ratios [45] and overload thresholds for broadcast TV receivers, contains spectral plots of UE emissions, one of which is extracted below.

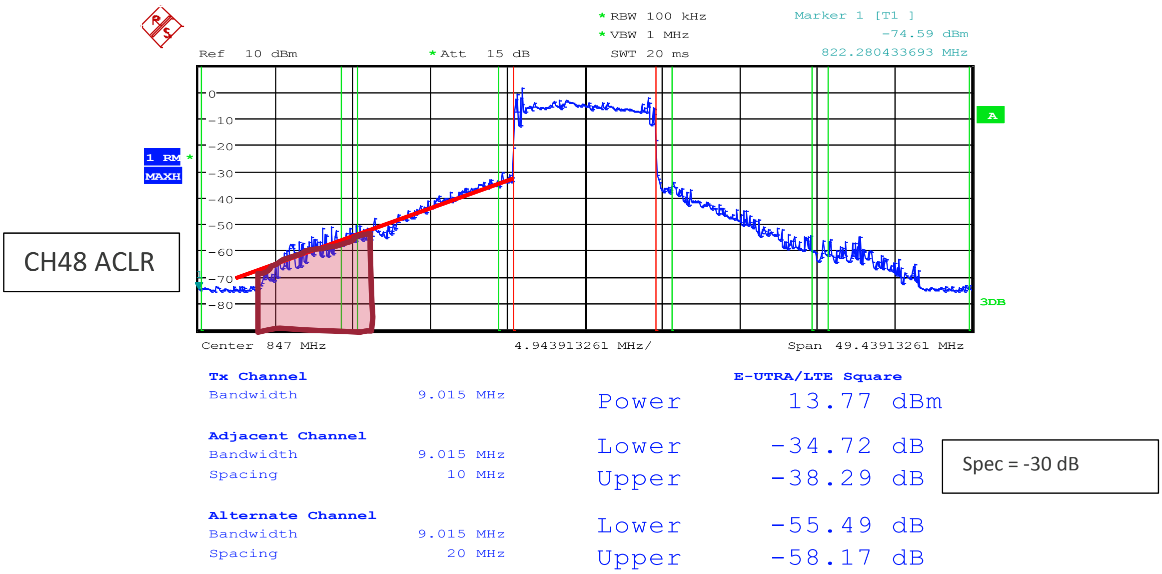

Figure 20: Spectrum of LTE UE operating at full power +23.8dBm (with a 10dB attenuator) [46]

As a test we integrated the power from -1MHz to -10MHz offsets. This gave a level of -21.79dBm, giving rise to an ACLR of:

$$ACLR = -21.79 - 13.77 = -35.54\text{dB}$$

This is within 1dB of the 34.72dB measured by the spectrum analyser. We can therefore integrate the power from -17MHz to -9MHz to determine the power which falls in CH48.

$$P_{CH48} = -30.24\text{dBm/8MHz}$$

The power in the highest 1MHz of CH48 was also estimated. This is the power in the bandwidth 693 to 694.

$$P_{693-694} = -34\text{dBm}$$

The ACLR in CH48 relative to an LTE carrier at a centre frequency offset of 18MHz can then be estimated.

$$ACLR_{CH48} = -30.24 - 23.77 = -54\text{dB}.$$

This is close to the ACLR presented in ITU-R BT.2215-3 Table 16 as shown below.

Estimated UE ACLR'

Offset	ACLR' dB with UE Full power / 20MBit/s LTE traffic loading
10 MHz offset	35.2
18 MHz offset	56.0
All other offsets	Not measured so 75, 85 & 90dB used as examples in this contribution

Table 16: Estimate UE ACLR [46]

This figure is considerably lower than the -32.2dB ACLR figure presented in ITU Document 4-5-6-7/55-E [16]. Emissions level estimates from the various sources are summarised in the following table.

Source	ACLR at 18MHz Centre Frequency offset between 10MHz LTE channel and 8MHz DTT Channel (dBc)
UTRA ACLR from 3GPP TS 36.101	-36.04
E-UTRA 20MHz ACLR from 3GPP TS 36.101	-33.72
E-UTRA 10MHz Channel ACLR from 3GPP TS 36.101	-30.73
ACPM-5017 Power Amplifier Specification	-34.2
ITU Document 4-5-6-7/55-E	-32.2
Report ITU-R BT.2215-3 embedded measurement results [Annex – LTE UE into DVB-T2 measurement]	-54
ITU-R BT.2215-3 Table 4 [Annex – LTE UE into DVB-T2 measurement]	-56

Table 17: ACLR emissions into DTT channel 48

The ACLR at 18MHz offset figures estimated from 3GPP ACLR figures can be considered to be worst case upper limits. Measured results indicate that it is possible to significantly improve on these figures, by possibly up to 20dB. These could be regarded as a lower limits as some margin would need to be added for implementation and temperature variations. However, UEs only need to satisfy the limits specified in the standards and whilst we expect real devices may improve on this we cannot assume they will do so by 20 dB.

Therefore, we will use the worst case ACLR estimated from the E-UTRA 10MHz channel case to estimate worst case filtering requirements in the DTT band and consider any additional margins when we have considered the feasibility of achieving the more stringent limits.

3.4 Emission level and filtering requirements estimation

We can use the worst case flat ACP assumption for a 10MHz channel to estimate the required filter rejection in the top channel of the DTT band.

The max emissions level for a UE can be estimated from the transmit power and ACLR as follows:

$$P_{TX} = 23\text{dBm}$$

$$ACLR = -30\text{dB}$$

$$ACP = 23 - 30 = -7\text{dB}/9\text{MHz} = -16.5\text{dBm}/\text{MHz}$$

Firstly we examine the APAC700 case. Assuming the ACP is flat vs. frequency to 688MHz, then the power in the top 6MHz wide DTT channel would be:

$$-16.5 + 10.log10(6) = -8.8\text{dBm}/6\text{MHz}$$

The APAC700 B28 emissions limit is -26.2dBm/6MHz. This gives a worst case filter attenuation requirement of:

$$Atten_{min} = -8.8 - (-26.2) = 17.4\text{dB}$$

The analysis in 3GPP TR 36.820 V11.2.0 section 7.3.1.1 [8] assumes a filter rejection of 15dB which seems reasonable given that in practice the ACLR will be better than specification by a certain margin and will further decrease with increasing frequency offset.

We can apply a similar approach to estimating the filtering requirement for the Region 1 case. Assuming the ACP is flat vs frequency to 686MHz and the ACLR is at its -30dBc limit, then the power in CH48 would be:

$$-16.5 + 10.log10(8) = -7.5\text{dBm}/8\text{MHz}$$

We use a figure of -52dB for the total coupling gain between the UE and a DTT RX as described in CEPT-ECC CPG-PTD(13)057. This document also gives a thermal noise floor for the DTT RX of -98.2dBm.

The assumed emissions levels and DTT thermal noise floor are shown graphically in Figure 21.

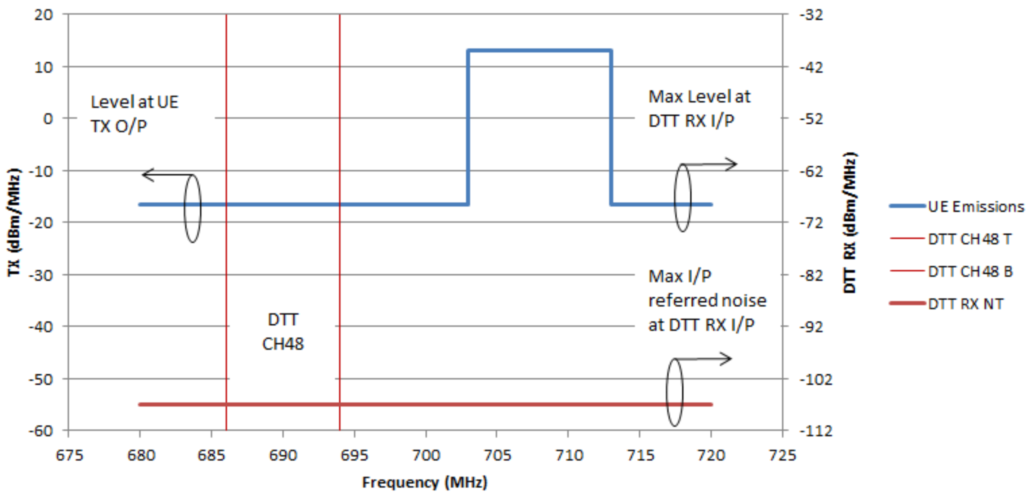

Figure 21: UE emissions vs. DTT Noise Floor

The filter attenuation then needed to push the UE emissions 10dB below the DTT RX thermal noise floor will be:

$$Atten_{min} = -7.5 - 52 - (-98.2) + 10 = 48.7\text{dB}$$

Assuming 3 dB insertion loss in the filter passband, the absolute attenuation required would be 51.7 dB at 694 MHz and below. It is unlikely that any UE would have worst case limit ACLR performance and flat emissions response outside the active channel, therefore it is likely the worst case absolute attenuation can be relaxed. As in the APAC 700 case, the maximum attenuation can be relaxed taking account of the expected ACP slope vs. frequency and ACLR margin vs. specification. This implies a filter attenuation of approximately 45dB worst case would be required in the Region 1 case to protect DTT at a level that is 10 dB below the expected DTT noise floor.

3.5 Design of duplexers and switches

In this section we have identified the key aspects of the design for duplexers, switches and filters). We discuss how the key technologies and design approaches to achieve the performance (e.g. dual duplexers) may impact on adoption and implementation into the UEs themselves.

3.5.1 Duplexers

Duplexers are used to combine the TX and RX paths to a common antenna path. The TX duplexer attenuates the TX Wideband noise in the RX band. A typical value for this RX isolation specification is -40dB. The RX filter attenuates the TX signal entering the RX path. A typical specification for this TX isolation is -50dB. These isolation figures are usually the most difficult specifications to achieve in a duplexer design.

Achieving these figures becomes more difficult as the duplex spacing is reduced. We have taken the sub 1GHz bands from the specification and compared duplex distances and ranked them in terms of difficulty (smallest duplex spacing as most difficult).

For comparison purposes we included the primary 700MHz band plans being considered and we split band 28 into its dual duplexer realisation. The table shows the duplex spacing and associated difficulty in achieving it in practice (1 = hard and 13 = easy) based on the increasing filter fractional bandwidth as the spacing between the uplink and downlink filter decreases.

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit			Downlink (DL) operating band BS transmit UE receive			Duplex Spacing	Difficulty
	F_{UL_low}	–	F_{UL_high}	F_{DL_low}	–	F_{DL_high}		
31	452.5	–	457.5	462.5	–	467.5	5	1
OP4	703		743	751		791	8	2
8	880	–	915	925	–	960	10	3
26	814	–	849	859	–	894	10	3
28	703		748	758		803	10	3
OP5	701		741	751		791	10	3
12	699	–	716	729	–	746	13	4
17	704	–	716	734	–	746	18	5
5	824	–	849	869	–	894MHz	20	6
OP2	698		733	753		788	20	6
28L	703	–	733	758	–	788	25	7
28u	718	–	748	773	–	803	25	7
OP1	703	–	733	758	–	788	25	7
27	807	–	824	852	–	869	28	8
18	815	–	830	860	–	875	30	9
19	830	–	845	875	–	890	30	9
61	830	–	840	875	–	885	35	10
14	788	–	798	758	–	768	40	11
13	777	–	787	746	–	756	41	12
20	832	–	862	791	–	821	71	13

Table 18: List of LTE frequency bands against band plan options and duplex spacing Op1 - Op4 represent the 700 MHz bandplan options defined in section 2.

From this we see that Options 4 and 5 are among the most difficult to implement of all sub 1GHz bands based on duplex distance and anticipated isolation requirements. SAW filters with fractional bandwidths of greater than approximately 5% are difficult to realise. The fractional bandwidths associated with the different filter options being considered are tabulated below. This indicates that options 4 and 5 would be difficult to implement as single duplexers.

	Gap to DTT CH48 (@694 MHz)			Uplink (MHz)		F_BW (%)	Downlink (MHz)		F_BW (%)	Duplex Gap		BW to Gap ratio
Option 1	9	1.29%		703	733	4.18	758	788	3.88	25	3.35%	1.2
Option 2	4	0.57%		698	733	4.89	753	788	4.54	20	2.69%	1.75
Option 4	9	1.29%		703	743	5.53	751	791	5.19	8	1.07%	5
Option 5	7	1.00%		701	741	5.55	751	791	5.19	10	1.34%	4
Option 6	9	1.29%		703	743	5.53	748	788	5.21	5	0.67%	8

Table 19: Frequency details of bandplan options [3]

We note that transition bandwidth to frequency ratio lower than 1% is impossible to achieve using SAW type filters and highlighted above in Table 19. However, this may be achievable using FBAR filters.

We note from our discussion with filter manufacturers that at fractional bandwidths above 5% the stop band attenuation deteriorates. Duplexers with fractional bandwidths of the order of 5% or greater are likely to be implemented with a dual duplexer architecture as depicted in the following figure.

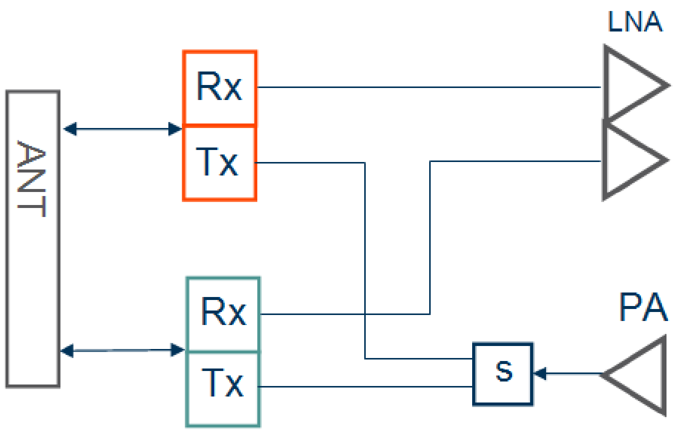

Figure 22: Dual duplexer block diagram

Usually duplexer corner frequencies are selected to be on a 5MHz grid from the band edge and the overlap region is selected to enable the widest supported channel bandwidth to be transmitted in any position within the band.

Dual duplexers are implemented in the APT700 band plan with a 15MHz centre overlap. This restricts the deployment of a 20MHz channel to the frequency ranges either 713-723 MHz or 728-738 MHz and corresponding downlink frequencies as shown in Figure 23.

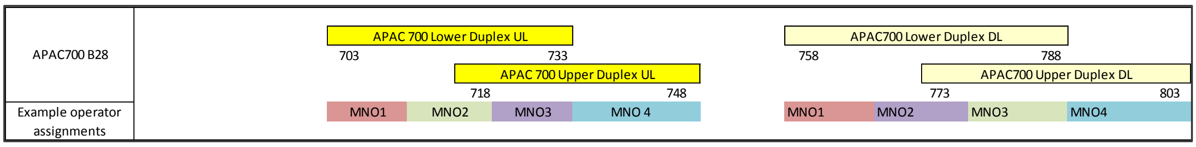

Figure 23: APT700 (band 28) Dual Duplexer Band Plan

[3] This has been assembled drawing on our confidential discussions with filter manufacturers.

Although dual duplexer approach can be used in the UE, there may still be concerns about band plan implementation in the base station. A general rule is that the ratio of filter bandwidth to duplex gap should be less than 5 where duplexers covering the whole bandwidth are required. We have shown the Base Station BW to Gap Ratio together with the band plan options being considered in Table 19.

Duplex spacing is also a concern regarding UE filter implementation but is considerably eased by adoption of a dual duplexer realisation. Implementing a dual duplexer is roughly equivalent in terms of cost and space requirements of adding another band.

In dual duplexer implementations there is a need for switches and in handsets that have multiple bands existing switched will be available. This includes additional poles available or the need for a new switch.

The implication of a switch when supporting dual duplexers needs to be considered in handsets that support a number of existing bands and also the level of diversity that the handset supports. However, if existing switches can be re-used to support the dual duplexer then there is unlikely to be any additional performance impact. In the dual duplexer configuration two poles are needed to support the transmit main antenna path and a further two poles for the diversity receive path.

Design of switches

Switches of up to Single Pole 12 Throw (SP12T) are currently available for mobile device front ends as is shown in the block diagram of the Skyworks SkyOne FEM below. A second switch is used in the diversity antenna path. Adding a new band to a mobile device requires extra switch ports for the antenna selection switches and either extra switches or extra ports on the RF Transceiver IC.

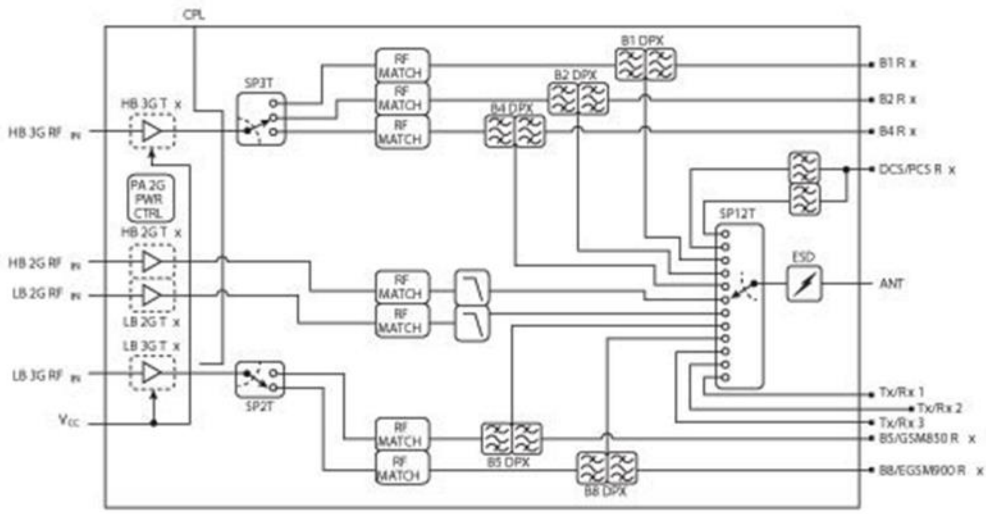

Figure 24: Skyworks SkyOne FEM

Metric	Performance impact
Insertion loss	Uplink: Can use more power but will reduce battery life Downlink: Can reduce the peak downlink data rate/cell range
Dual duplexers vs. Duplexers	Same complexity as if introducing additional band.
Linearity	Intermodulation products impacting active receive bands particularly into active cellular, Wi-Fi and GPS bands
Availability of space in handset	Difficult to accommodate increased number of bands/filters/switches because they take up more space. Integrated modules can be difficult to accommodate in handsets where space is limited

Table 20: Summary of performance impacts of the RF front end

3.6 Future of filter development

In this section we examine the future of filter development whose focus currently is on minimising the number of duplexers in a radio per antenna.

Filter manufacturers are working on tuneable filters for future handset applications. The industry indications are that tuneable duplexers will be introduced within the 2018 timeframe. Both current filter manufacturers and new entrants such as Wispry [47] are conducting R&D on this topic. Tuneable filters will reduce the duplexer and switch count in a handset RF Front End. This means a reduction in the overall integrated circuitry and efficient use of the electronics and battery power. Tuneable duplexer filters can have narrower bandwidths than conventional filters. This is because they need only cover the maximum channel bandwidth supported by the mobile, typically 20MHz, and not the full band which would typically be in the region of 30MHz to 75MHz.

Likely implementations are 3 duplexers per antenna path, one for the low bands, <1GHz, one for medium bands, 1GHz to 2.2GHz and one for high bands from 2.3GHz up to about 3GHz.

Tuneability is beginning to be introduced with Antenna Tuners already deployed in Mobile Handset RF Front Ends. However, technical challenges remain to be solved in order to implement tuneable duplexers. The additional flexible tuning constraint makes it more likely that the stopband attenuation will be less than conventional implementations.

The ability of a tuneable duplexer filter to achieve higher close in attenuation than conventional SAW or BAW designs while passing a signal in the new Region 1 band is unclear. Our opinion is that it would be unlikely that the stop-band performance would be better than SAW or BAW implementations as the tuneability requirement adds a further constraint to filter design.

Since this study is trying to achieve stringent limits and these are more likely to be achieved with current technology we will restrict this study to the limits achievable by non-tuneable filters.

3.7 Unit costs for filtering technologies

The filter ecosystem for handsets is made up of a number of vendors that supply the main handset vendors across the mobile industry such as EPCOS, AVAGO, Triquint and Murata. Figure 25 shows the market share across the four main filter vendors with Epcos the leasing SAW vendor and Avago the leading BAW vendor. However, both Murata (SAW) and Triquint (BAW) are the second dominant players in their respective filter technology sectors.

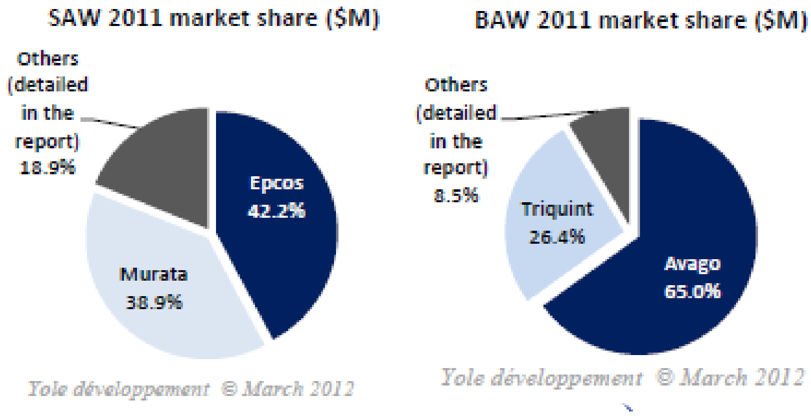

Figure 25: Market share across filter vendors [47]

The designs for filters and the development of technology are influenced by:

- Commercial drivers and business case of handset vendors
- Choice and number of frequency bands and bandwidths supported by handset vendors
- Available space in handsets
- Power consumption

Industry discussions have revealed the following ballpark insights into part costs. We have assumed that enough receive ports are available on the RFIC and assuming switch ports are available. Switches with up to twelve ports are now available.

Unit costs for filters as described in the sections above i.e. discrete components that can be incorporated into handsets, are described relative to a low complexity SAW duplexer in the following table. These estimated cost relationships are based on current technology and are typically below $1.

Filter technology	Estimated relative cost (US cents)
SAW (Low Complexity)	Baseline reference cost
SAW (High Complexity)	Approximately 2 x reference cost
BAW (FBAR)	Approximately 4 x reference cost

Table 21: Filter technology costs (RW & Benetel Estimates)

The above unit cost relationships are based on moderate volumes in the low millions (<5 million).

In addition to the filter costs it is important to note the stand alone Power Amplifier for new band is similar to the upper range costs of the SAW filter.

3.8 Technology vs. performance trade-offs

The typical insertion loss between a PA output and the antenna is 4dB. Integrating the duplexer with a PA in a combined PA-Duplexer Module can reduce insertion loss by 0.3 to 0.5dB. As insertion loss increases, for example because of additional duplexer loss or switch loss, the PA design must be adapted in order to maintain the required 23dBm output power.

The additional insertion loss will then result in additional PA power consumption and a consequent reduction in handset battery life as shown in Figure 26.

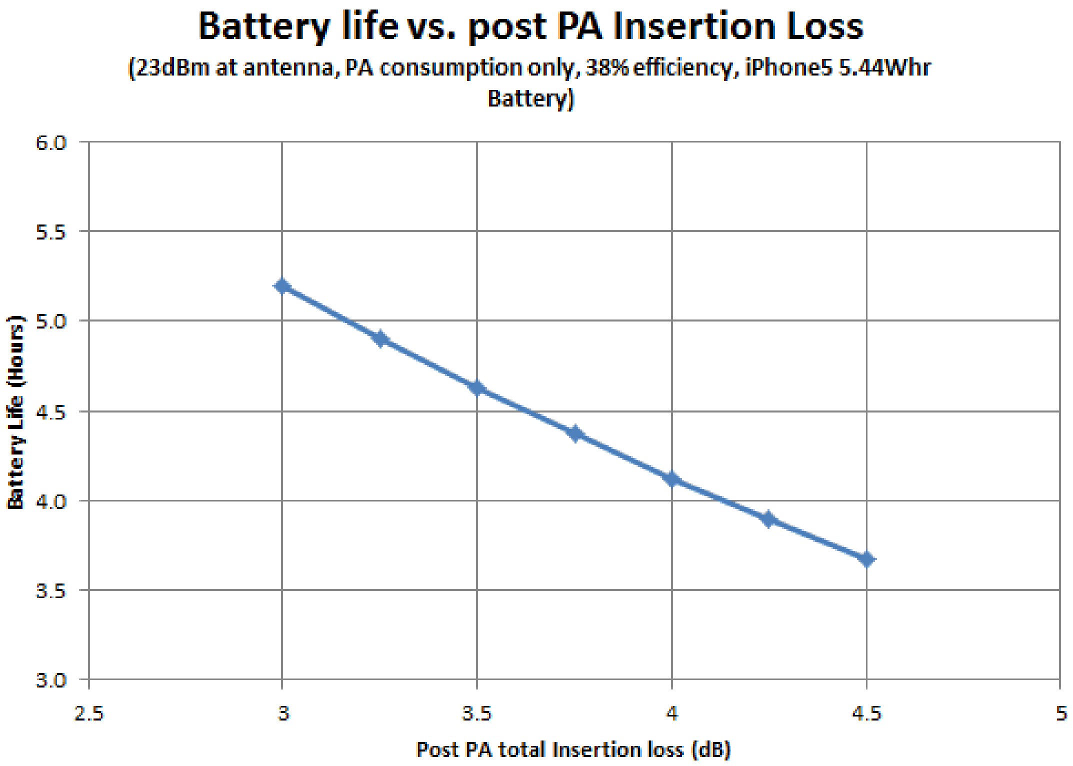

Figure 26: Insertion Loss vs. Battery Life

The Insertion Loss vs. Battery life plot in Figure 26 is based on a current Triquint TQM700013 B13 PA with an efficiency of 38% at a max output power of 27.5dBm. This would permit 23dBm output power with 4.5dB post PA loss. In cases where lower post PA loss was present, a lower powered PA could be used in order to maintain efficiency around 38%. Note this shows only the contribution of the PA to battery consumption: although there are other sources of energy demand, the PA is often the most significant contributor.

Envelope Tracking (ET) is emerging in new Multi-Mode Multi Band PA architectures. ET is expected to provide significantly higher efficiencies. The objective of envelope tracking is to improve the efficiency of PAs carrying high peak to average power (PAPR) signals. The drive to achieve high data throughput within limited spectrum resources requires the use of linear modulation with high PAPR. Unfortunately, the efficiency of traditional fixed supply PAs when operated under these conditions is very poor. The efficiency of an ET PA is improved by varying the PA supply voltage in synchronism with the envelope of the RF signal. Although, more detailed analysis would be necessary, ET has the benefit of reducing ACLR compared to current fixed supply power amplifiers which should make filter implementation easier in multi-band multi-mode handsets.

Stopband performance degrades as filter bandwidth increases. This is the most significant trade-off challenge in the design of duplex filters for the 700MHz band. Filters of 40MHz or greater have a risk of poor rejection artefacts in the stop band close to the pass band and also lower rejection further out, e.g. hundreds of MHz away from the passband.

There is some small increase in filter insertion loss with increasing bandwidth. This is influenced by filter technology and implementation. In the cases we discussed with filter manufacturers they have predicted insertion losses of less than 3 dB for 30MHz filters. In addition to degraded stop band performance filters with bandwidths of 40-45MHz have increased insertion losses up to about 4dB.

3.8.1 Performance between insertion loss and wideband attenuation

In addition to insertion loss and close-in attenuation consideration must also be given to wideband attenuation performance of the filter. This affects both isolation in the RX band and attenuation in the DTT bands. There is a risk that as more of the filter's resonator elements are used to achieve the close in attenuation, the wideband attenuation may decrease.

Filter manufacturers specify separately the close-in and wide band attenuation. Example plots from 2 band 20 filters, the Triquint 856979 and the TDK-EPCOS B8509 follow.

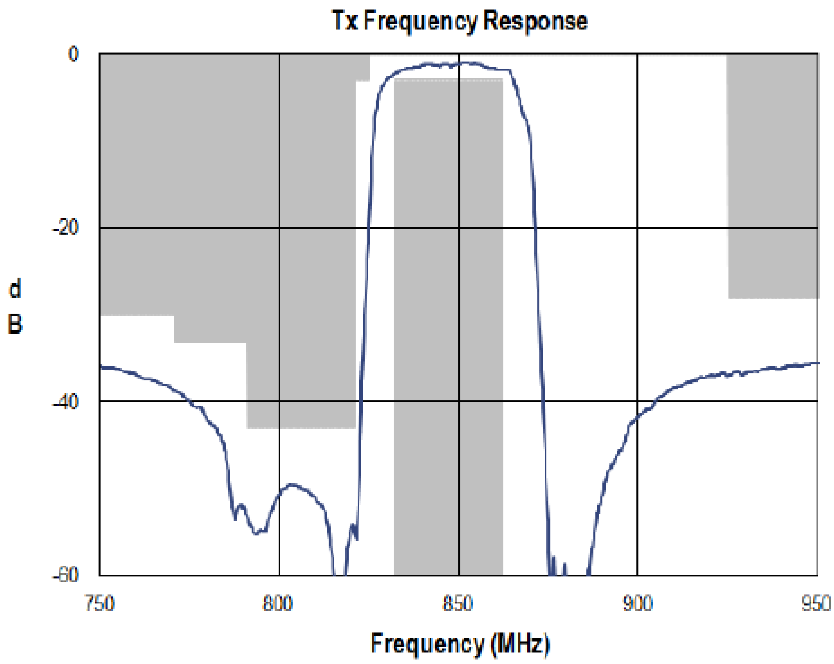

Figure 27: Triquint 856979 Close-in Specification Template [48]

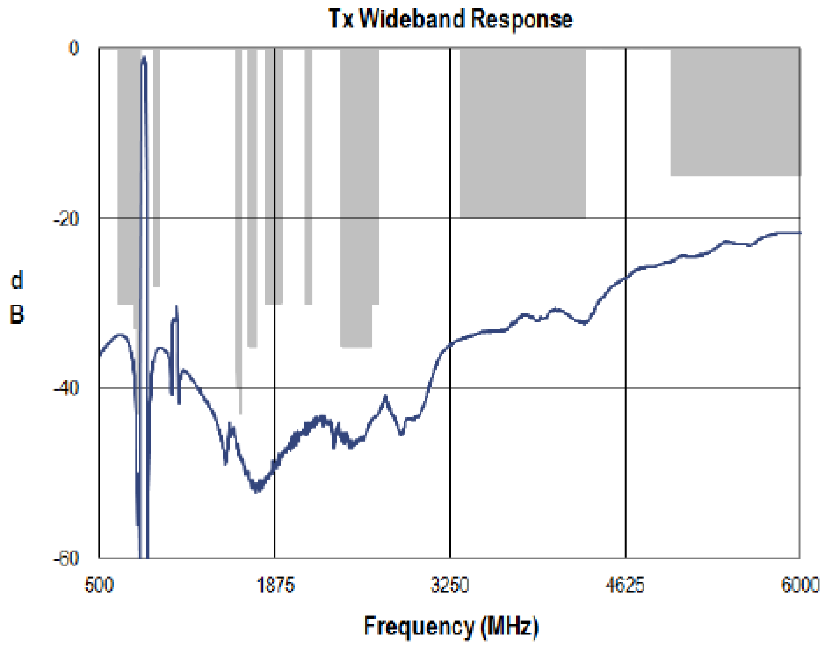

Figure 28: Triquint 856979 Wide Band Specification Template [48]

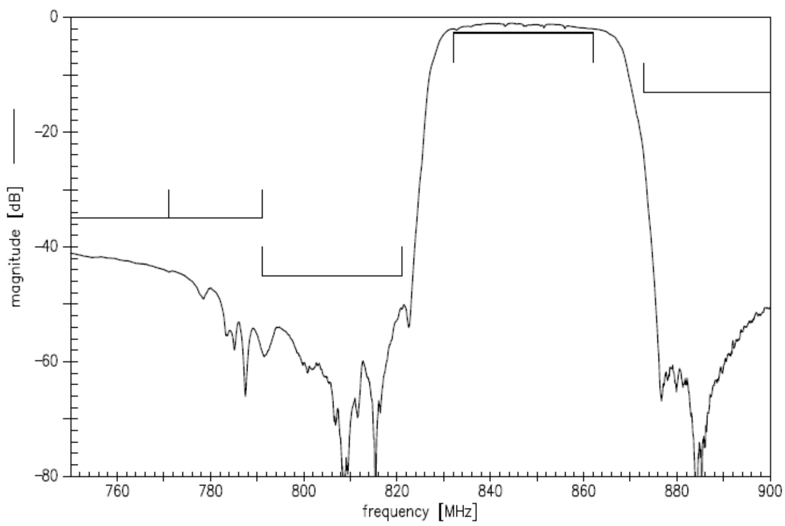

Figure 29: TDK-EPCOS B8509 Close-in Specification Template [49]

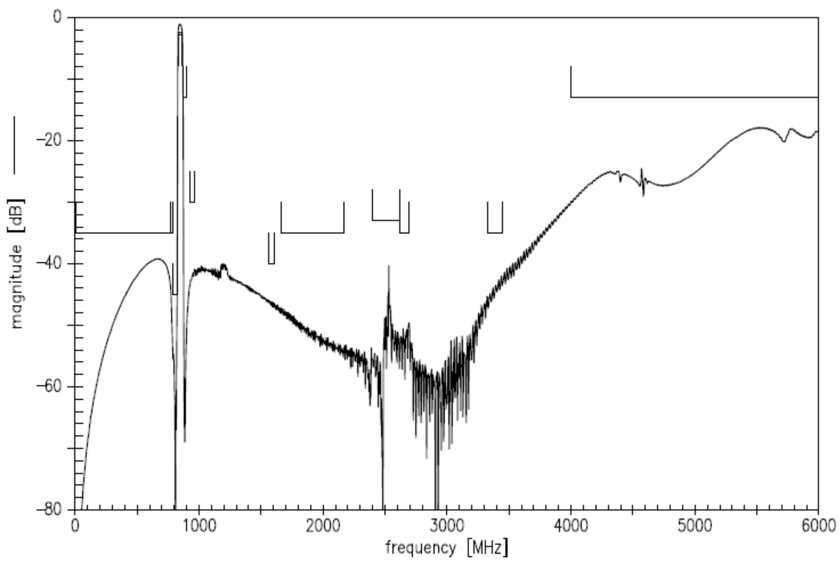

Figure 30: TDK-EPCOS B8509 Wide Band Specification Template [49]

From these representative plots we can see that the wideband attenuation achieved is less than the close in attenuation.

The attenuation in the RX band, 791-821MHz, for these filters is 43 and 45dB min. The wideband attenuation is less than this amount. For example the minimum attenuation in the 2.4GHz Wi-Fi band for these filters is 33 and 35dB. The minimum attenuation on the low frequency side of the pass band in the region 10 to 771MHz is 30 dB.

In considering the protection of the DTT bands we also need to consider the wideband attenuation applying to the lower channels in addition to the close-in attenuation in Channel 48. The emissions from the power amplifier will decrease as frequency separation from the carrier increases. However, according to one filter vendor they mentioned there was some variation in how quickly the ACLR dropped off with increasing frequency signals. This is due to the variability in the bandwidth (1.4, 3, 5, 10, 15 and 20 MHz) and in the variability of the UE Resource Block assignments in each channel bandwidth. This fall off is not as steep as in the WCDMA cases and thus there is still some uncertainty as to the impact this will have in handsets.

Some of the filter manufacturers interviewed indicated that the wideband attenuation response might degrade as more close-in attenuation is provided in a filter. As a result we examined the specified minimum wideband attenuation performance vs. steepness of the pass-band to stop-band transition for 19 SAW filter types from 3 different manufacturers and plotted the result below.

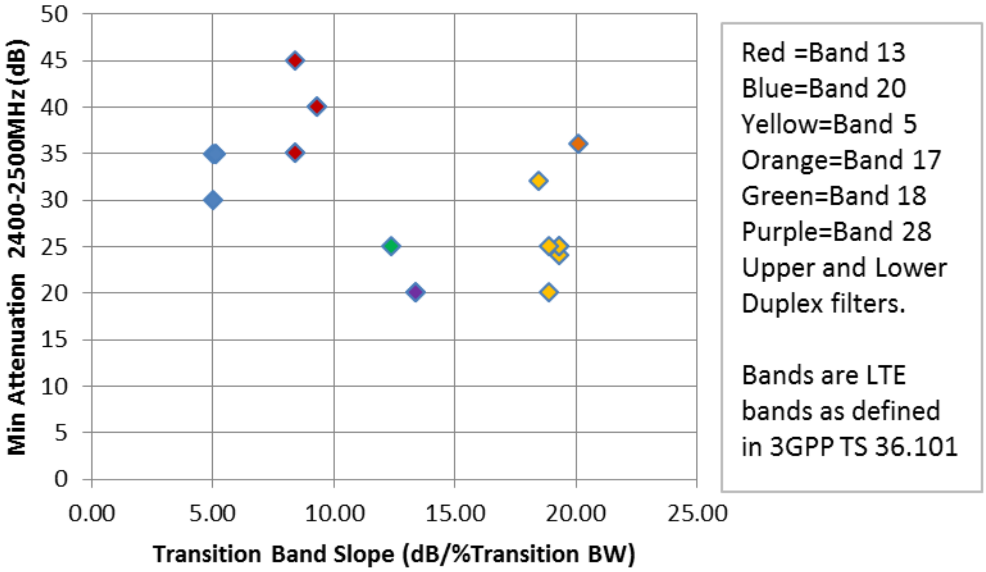

Figure 31: Minimum Wideband Attenuation (in 2400-2500MHz) vs. steepness of the transition from pass band to stop band for 19 duplexer transmit filters

These data indicate that for steeper transition band slopes, less wideband attenuation is likely to be achievable. However, it is recognised that more complex filter implementations may be able to achieve specific wideband performance targets and steepness targets.

We note that any practical RF front end design would therefore need to take into consideration the wideband filter performance coupled with the PA frequency response satisfied both wideband attenuation and close-in attenuation.

3.9 Liaison with filter manufacturers

In this study we have liaised with the filter manufacturers to gain intelligence regarding the technical aspects of filter technology, performance and costs. We held discussions with five main filter manufacturers to obtain the key data points to respond to the five questions posed by the study.

We have used the vendor information throughout this report however, the notable messages are summarised below:

- Option 1 is easily met. Option 2 is difficult and options 4 and 5 are very difficult. Options 4 and 5 would most likely require a dual duplexer implementation.
- The most challenging aspect of filter implementation is achieving the stop-band performance at 694 MHz and even 698 MHz where the transition from the pass-band is short in frequency range.
- A general 'rule-of-thumb' is that 10MHz of separation is needed in order to achieve 20dB of attenuation. Thereafter the filter response falls of quite rapidly. Note in the APAC700 case, the transition region is 703-694=9MHz and the attenuation figure assumed in the 3GPP document TR 36.820 is 15dB.
- The typical duplexer TX and RX isolation figures are 45 to 50dB where TX-Isolation, i.e. RX filter attenuation at the TX frequency is usually has the most demanding requirement. This is generally a more difficult challenge to meet than increased passband insertion loss resulting from wider fractional bandwidths in representative designs.
- Some relaxation of the pass-band insertion loss at corner frequencies may be permitted to facilitate filter realisation.
- Manufacturers have been developing solutions that can meet both the APT700 band plan using dual duplexers and in one case can also meet the 2 x 45 MHz bandwidth case in the 700 MHz band but not at the more restricted limits proposed by the UK/CEPT.
- Vendors suggest that using a dual duplexer with a 2 x 30 MHz arrangement to meet the restricted limits proposed by UK/CEPT (option 1 and 4) can be achieved with existing technology.
- The new option 6 would be difficult to achieve due to the narrow duplex gap. This could be implemented as a dual duplexer. However the duplex gap is too narrow to permit a full band Base Station Duplexer implementation. 45dB attenuation at 9MHz offset can be achieved with some SAW implementations and can be achieved with FBAR implementations.
- 45dB attenuation at 6MHz offset can be achieved with FBAR and possible BAW but not with SAW filters.
- Filter wideband performance needs to be taken into account in addition to close-in stopband attenuation performance.

3.10 Technical filter analysis summary

This chapter has analysed the technical details and performance of current filter technology being integrated into handsets today. Filter technology is progressing in a way that can already support more stringent ACLR/OOB emissions beyond the 3GPP specification into DTT. This suggests that handset vendors currently have a choice to incorporate filter technology that can support the 700 MHz band in any of the proposed band plan options and the required European OOB emissions at a price point that is likely to be only marginally (if at all) more than existing solutions if purchased in high enough volumes.

There is also potential for increased competition, as only two out of the four vendors can commit to their technology being able to achieve the increased OOB rejection into DTT with existing technology. Once any of the other vendors introduce their products that can achieve these limits, this is likely to drive the price of filters (to handset vendors) down further.

Overall the technical filter issues to achieve the stringent protection to DTT indicated in the UK/CEPT input paper are achievable with existing technology. Integration of high rejection filters into increased multi-band integrated designs such as the Qualcomm RF360 will only come after integration within agreed specifications. Agreement of these specification is therefore not just a technical barrier but also requires industry ‘buy-in’. Since existing technology can achieve the required limits the cost of a mass market product will be driven by the silicon area required, market size and yield.

Developments in technology suggest features such as envelope tracking and more integrated devices will help improve handset performance. Therefore, by 2018 we would anticipate a filter ecosystem to emerge that would be well established with products available to support multiple bands including 700 MHz and flexible enough to support different and multi-band configurations.

We examine in the next chapter the key issues in terms of market scale. For example, we analyse whether there is sufficient market scale for vendors to just serve Europe or if a larger market is required before vendors would commit to a regional bandplan for 700 MHz.

4. Multi-band handset ecosystem analysis including 700 MHz band

4.1 Survey outline

Device availability will be a critical factor in operator support for any new bandplan. A series of interviews was carried out for this study with key device manufacturers and their chip and RF suppliers to gauge their likely level of support for:

a. The baseline APT 700MHz band plan
b. A potential EU variant of the band plan, involving dual duplexers to achieve 2x40MHz rather than 2x30MHz bandwidth.

In total, 25 stakeholders were interviewed, all of them active in LTE mobile devices and with global reach, and therefore the ability to drive and influence the whole ecosystem.

All the conclusions and data points included in this section, unless otherwise stated, are based on the results of the survey of stakeholders combined with qualitative discussions with them.

This chapter takes 2014 and 2018 as its key time points – 2014 will see the first wide scale APT700 roll-outs taking place, plus a new wave of auctions; 2018 is the earliest date at which European operators are likely to acquire spectrum in this band, and many regulator and carrier decisions at that point will be influenced by the state of the device ecosystem.

4.2 Current patterns of LTE band support

According to vendors, LTE bands are generally being assessed for device support in three layers:

- Layer 1 – global, relatively standardized band plans (though usually excluding North America) e.g. APT700MHz, 1.8GHz, 2.6GHz
- Layer 2 – bands with almost universal harmonized adoption in a large region, and where this spectrum drives the first wave of LTE roll-out e.g. USA 700MHz and AWS, EU 800MHz, 2.3GHz and 2.6GHz TDD, other Chinese bands
- Layer 3 – bands which will primarily still be used for other technologies in 2018, or which are specific to a small group of carriers. These will still be considered by many OEMs but usually with proof of strong operator support/investment, and often at higher device cost e.g. 850MHz, 900MHz, USA 1.9GHz, 2.1GHz

As Figure 32 indicates, in 2013 the most commonly supported LTE bands are US700MHz (Verizon and AT&T variants); 2.6GHz and 800MHz. In the early stages of LTE, band support has been driven by:

- Band plans adopted by early movers most notably Verizon (US700), European leaders (mainly 2600/800), China Mobile (TDD). Some carriers put significant investment into funding the initial ecosystem and first generation handsets carry premium price
- Bands with the earliest prospect of achieving scale, i.e.

- those being widely auctioned in a harmonized way. The European 2.6 GHz and 800 MHz bands fall in this category as, in 2013-14, they create one of the largest harmonized addressable bases
- those being adopted cross-regionally especially the 1800 MHz band, which bodies like GSMA see as the single most harmonized band on a global basis

Most LTE bands have regional variations in 2013. Important examples include:

- 2.6GHz has significant variations in how it is split between TDD and FDD, and there has been far greater focus on the TDD aspect in USA and Asia than in Europe
- The European 800MHz plan has variations from that of APAC.
- USA 700MHz is very different from APT700 and fragmented within itself

That has been a challenge for OEMs, but most tier one vendors have been willing to support a large percentage of the available variations because:

- First wave LTE devices carry a premium
- Operators have injected funding into creating device bases for their particular band(s) e.g. Sprint in 1.9GHz
- As LTE roll-outs remain relatively rare, the total number of regional band variations remains manageable.

Changes in the band plan approach by 2018:

The situation will change considerably by 2018. Premium prices and first mover advantage will be replaced, as key drivers for supporting a band, by scale. This will be for several reasons:

- As the 'LTE premium' disappears and smartphone prices come under increasing pressure, the scale of the addressable market will become an increasingly important factor for most OEMs, especially in the lower end market.
- There will be a far larger number of commercial networks, using a wider variety of band plans (e.g. China and Latin America). Therefore each individual band plan will command a lower percentage of the addressable market and be less valuable than in 2013. E.g. in 2012 Verizon's peculiar 700MHz plan accounted for about half the devices sold, but by 2018 there will likely be over 300 networks live.
- OEMs will increasingly select only those variations which deliver sufficient scale and/or premium.

The larger the region over which they are harmonized, the greater support they will attract from OEMs. The best example will be 1.8GHz, expected to be harmonized to a greater extent than any other (everywhere but North America).

As the ecosystem develops, a small subset of LTE bands will emerge which support a generic 'worldphone' platform – an off-the-shelf set of bands which will be implemented in any handset that is targeted to be sold internationally (excluding North America). These platforms will deliver the most attractive volumes and costs for mass market vendors. Consensus among stakeholders, GSMA and many operators is that these default bands, by 2018, will be:

1800MHz, 2600MHz, APT700MHz, EU800MHz, plus key TDD bands in most cases. These will be implemented in large numbers of handsets, whether or not the band is activated. Therefore, by 2020 we expect a majority of handsets available in the EU to support APT700 even if this spectrum cannot be used in the EU. This will support LTE roaming in the APT region. For consumers, this is likely to be the main attraction of 700MHz being included in smartphones (though 1800MHz will be a more important global roaming band).

US bands will not be implemented as standard in phones for global distribution, neither will EU-specific bands such as potential EU700. These more specialized bands will appear in region specific models which will be driven mainly by the level of operator support.

As a result, by 2018, APT700 will be in the global top three bands in three important respects for OEMs' frequency support decisions:

- Total addressable market for devices
- Number of carrier networks commercially deployed
- Low cost of components (as a result of the above)

The consensus of OEMs, backed up by projections by the GSA, Rethink and other research firms, is that the top three bands in all these respects by 2018 will be 1.8GHz, 2.5/2.6GHz (FDD) and 700MHz (excluding US variants).

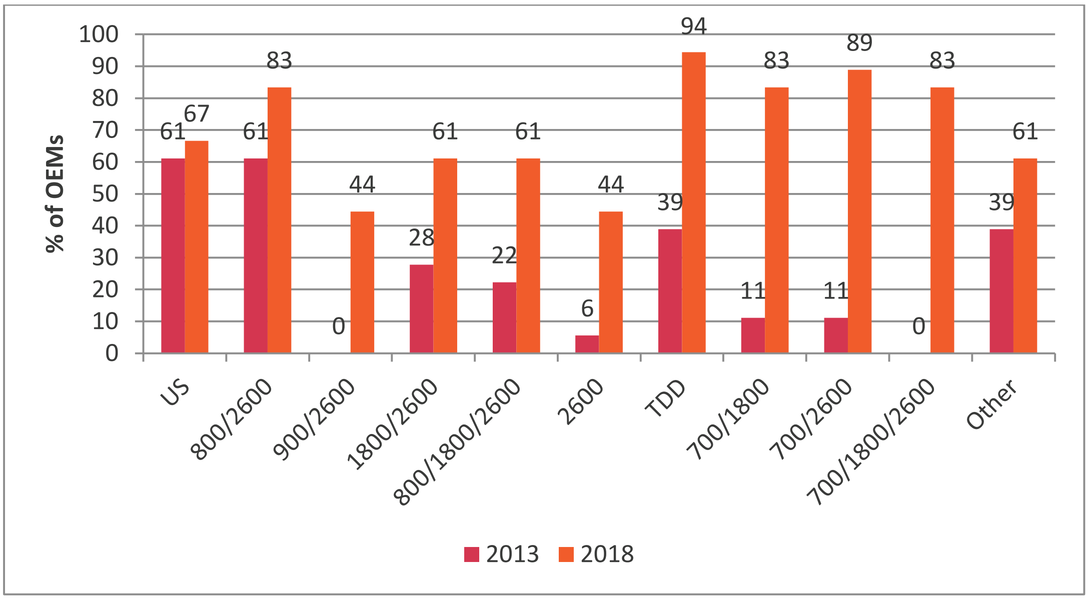

Figure 32: Percentage of device suppliers supporting the top LTE band combinations in 2013 and 2018. Note these may often also be combined with 3G or 2G bands, but these are not analysed in this study.

As Figure 33 indicates, the APT700 option will overtake the US 700MHz band plan, and the EU 800/2600 combination, as the band supported by the largest number of device suppliers, by 2018. It will almost always be deployed in combination with a higher frequency, most usually 1.8GHz, 2.6GHz or both.

The figure clearly shows the development of a mass market for LTE devices during this period, with every respondent increasing the number of LTE segments in which it operates. It also clearly shows the shift of volumes towards the Asian bands, because of the high volumes in that region (especially when harmonised with Latin America).

While 72% of vendors will support the EU's 800/2600 and/or triband options, even higher numbers will support APT700 in various combinations by 2018. In fact, every vendor except one expects to support at least one APT700MHz combination by 2018. The other highly supported group of bands will be the main TDD options (2.3GHz and 2.5GHz bands, mainly because of China and India). It is notable that the respondents which are most likely to prioritize APT bands over European ones (even established 800/2600 options) are the Chinese low cost players, which will account for a rising proportion of the handset ecosystem through the period of the study.

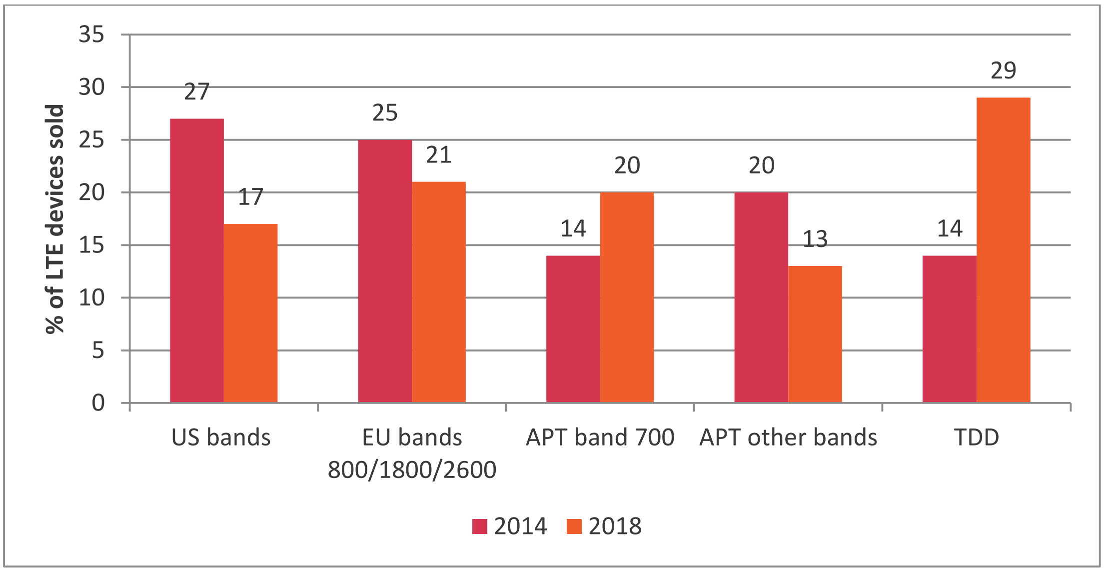

Figure 33: OEM expectations of the % of their LTE device shipments which will fall in each major set of bands, 2014 and 2018 (consensus view)

Figure 33 summarizes the vendors' projections for how important each major LTE regional family of bands will be in their future handset shipments. Unsurprisingly the US bands decline as a percentage as their operators' early and aggressive deployments stabilize in growth terms, and other regions accelerate LTE roll-out.

The two groups of bands which will drive the greatest growth – in a far larger total market of course – will be APT700 and the main TDD flavours. This indicates again how important Asian carriers' choices will be in deciding the shape of the future LTE map and the OEMs' strategies. In 2018, 62% of shipments will be in bands that are primarily driven by the Asian market, even though they may also be supported elsewhere.

4.3 The addressable market to 2018

No commercial roll-outs of 700MHz LTE have taken place in Asia-Pacific at the time of writing, but by the end of 2014, several significant deployments will have taken place and the device ecosystem will be gaining a level of critical mass (see section 4.5 on total addressable market). This is based on the numbers of LTE subscribers with access to the band and we assume the average LTE subscriber will have 1.8 devices by 2018.

There is broad support for the APT700 band plan because it is being adopted in its baseline version by a large number of countries in Asia-Pacific and also in Latin America. The scale of the addressable market will depend on whether/how far China and India adopt harmonized band plans in 700MHz.

As Figure 34 shows, if both those giant nations were to support baseline APT700, the addressable market for LTE devices would be over 610m subscribers, while even if neither did so, it would be still be over 331m in early 2018 (about 35m larger than the European Union’s total LTE addressable base at the same date). In addition, users are forecast to have 1.8 LTE devices each, as a global average, by 2018 (Cisco).

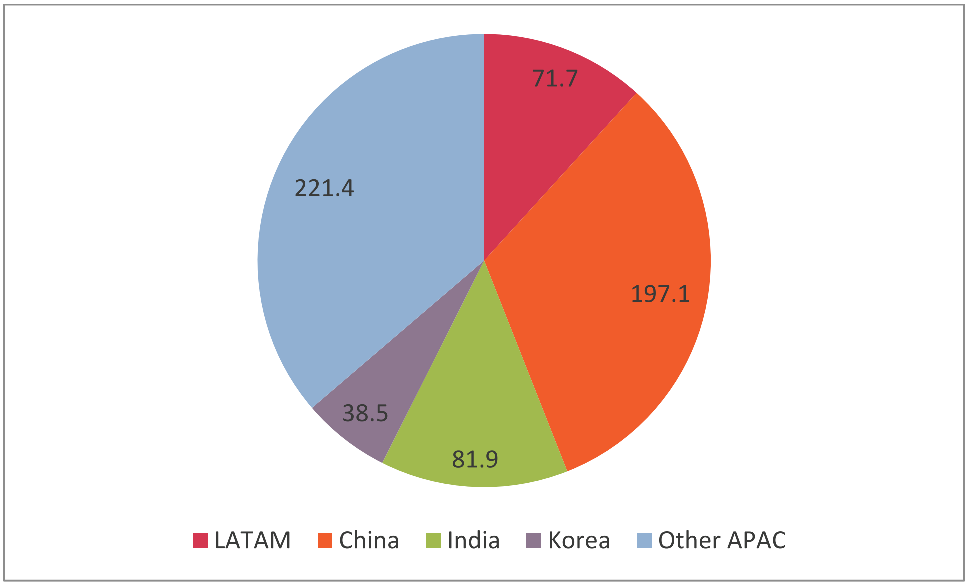

Figure 34: Forecast addressable market for APT700 LTE devices by 2018 (excluding M2M devices and assuming support in China and India)

This potential market size creates considerable economies of scale, especially as, in the majority of these countries, 700MHz will be allocated as the first sub-1GHz band, suited to broad coverage. Therefore it is likely to take on the role of primary roaming band in these regions, for domestic and also international roaming. That means it will be supported almost by default in most devices once the spectrum starts to be allocated.

This contrasts with the situation in Europe, where 800MHz has been allocated as the first sub-1GHz coverage band. That raises the issue of whether 700MHz will ever have such a prominent position in spectrum strategies in Europe as it does in Asia-Pacific and Latin America.

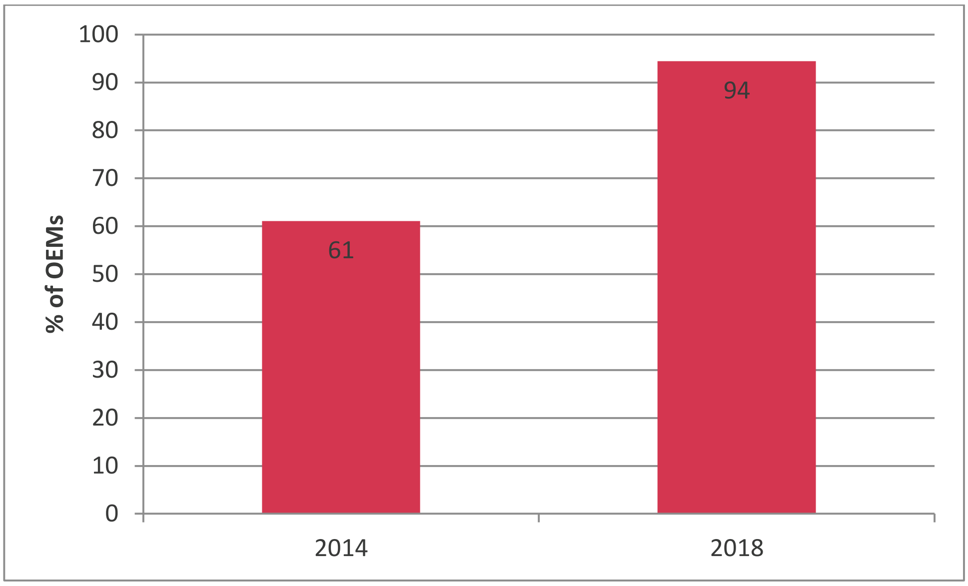

Figure 35: Percentage of handset makers planning to support APT700 in 2014 and 2018.

For the reasons sketched above, the majority of handset makers will support APT700, usually in combination with other bands, at an early stage and in mainstream, high volume devices. Figure 35 shows that over 60% of the major OEMs and ODMs surveyed plan to support APT700 in commercial products by the end of 2014, and 94% in 2018. By contrast, about one-third of respondents would expect to support an EU-only 700MHz variant (see section 4.5.1). The only companies which do not plan to support this band are those entirely focused on a different regions e.g. North America.

The APT700 will be supported in the majority of phones by default but no other variants of 700 MHz will be a default option. In other words, there are three possible scenarios for Europe:

- If no 700MHz spectrum is released, a majority of handsets (estimated 75%) will have APT700 support by default anyway
- If APT700 plan is adopted, those handsets will be available to European operators
- If Europe adopts its own variant, an 'EU700' plan will need to build up OEM support

More details on these outcomes are given in section 4.5

4.4 OEM willingness to support non-mainstream band plans:

As outlined above, the LTE picture will continue to fragment, forcing OEMs to choose between a growing variety of combinations, a shift which will lead to some changes in strategy. Figure 32 shows the continuing fragmentation of the LTE spectrum picture. In 2013, 40% of OEMs are supporting 'other' bands or combinations beyond the dozen which are expected to be supported by all OEMs during this period. In 2018, the proportion of OEMs supporting non main-stream band plans will have risen to two-thirds, indicating a rising willingness to support second-tier combinations.

This will be the result of several factors, as revealed in conversations with the vendors:

- Technological advances which will make it simpler and cheaper to support a larger number of bands e.g. wideband antennas, RF advances such as envelope tracking (e.g. Qualcomm RF360)
- Technological advances to reduce the power consumption of supporting multiple bands
- Advances in cognitive or adaptive radio, which can move intelligently between bands, though this will still be confined to premium products by 2018
- The switch-off of 2G or 3G networks by some LTE operators, freeing up a band for an additional LTE option

However, a closer look reveals that, while more OEMs are willing to support a band that is not fully mainstream, the average number of 'other' frequency combinations they support will have fallen from six to two. In other words, vendors will have become more reluctant about taking on an additional band, despite the factors outlined above, and will only venture outside the global or near-global combinations with a strong cost/benefit analysis.

By 2014, the average device maker will be supporting 10 LTE band combinations, though the total varies wildly from 21 to just three in this immature space. Only a few OEMs have the resources to mount a truly global LTE strategy at this early stage, and so some are confining themselves to a particular region in this early phase.

By 2018 all the respondents will be working across most major regions, and on average, expect to support 12 combinations. Almost 40% expect to have added new band combinations by then, but 17% actually hope to support fewer options by 2018, shifting their resources to the devices with greatest scale as handset margins fall.

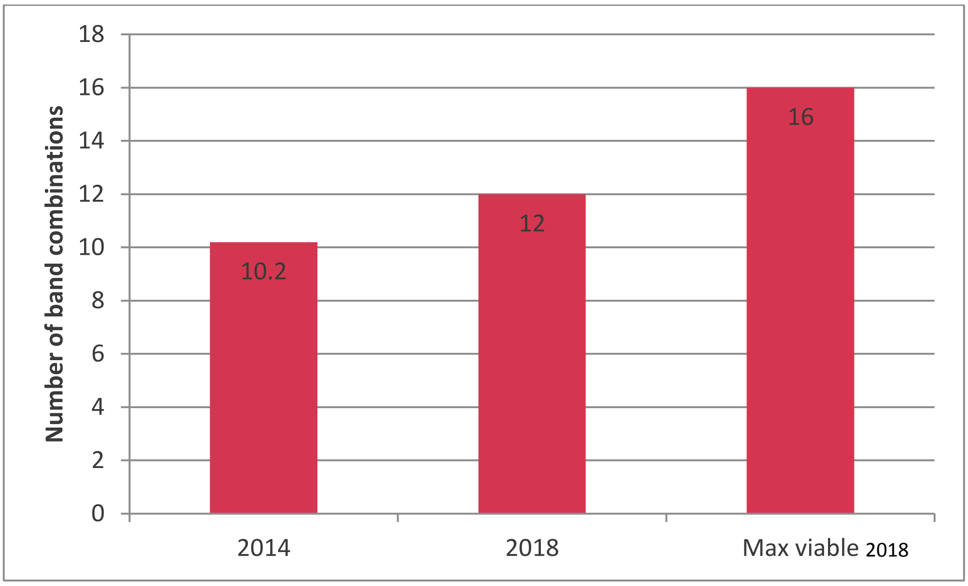

Figure 36: Consensus view from respondent base of device suppliers – number of LTE band combinations supported in 2014 and 2018, and the maximum considered commercially viable for a global vendor in 2018.

Overall then, OEMs are cautious about how many LTE bands they will be prepared to support, and expect the justification bar for adding a new one to become higher as options multiply and handset margins fall. They will increase the range of options they cover only slightly, on average, during the period (Figure 36), even though many new networks will be rolled out in that time, in various new bands.

The consensus view is that 16 device profiles would be commercially viable in a global space, but this is still a small percentage of the scores of combinations that could potentially be supported by operators by the end of the decade. By then, other new options such as 450MHz and refarmed 2.1GHz will also be vying for support, for instance.

Note: the survey concentrated on providers of mainstream consumer or enterprise handsets and tablets, with global or major regional reach. A different view would have been obtained from OEMs focused on smaller geographical areas or on specialized/vertical market devices such as those for public safety. In these segments, there would be higher acceptance of the need to support unusual bands, as these vendors would target smaller volumes with higher margins and a greater degree of customization.

Apart from the sheer number of choices, there are other factors which will make it hard for a non-global band plan to attract wide-scale vendor support.

4.4.1 Operator support

Device choices are always something of a chicken and egg situation, with most suppliers reluctant to move without clear operator support, but carriers basing their own decisions partly on device availability. Early LTE bands have been driven by flagship carriers which have invested heavily in kick-starting a device ecosystem (e.g. Verizon Wireless in US 700MHz, SK Telecom in multiband LTE-A). Sometimes this can be enough to promote an obscure band up the OEMs' priority lists, an extreme example being China Mobile's TD-LTE efforts.

The OEMs believe that, by 2018, most new LTE bands will be second or third wave, and therefore incremental rather than strategic. These are unlikely to attract the same level of operator support and financing as the first bands. In Europe, 700MHz falls into this category, with 800MHz being the key band for first wave LTE roll-outs, sub-1GHz coverage and roaming (see below for more detail).

4.4.2 Complexity

On one hand, it will get simpler to support a larger number of band plans by 2018, because of advances in RF, antenna and other technology. On the other hand, those effects will be offset by even greater complexity of the next wave of LTE devices, with additions such as

- New iterations of MIMO, e.g. 4x2 in LTE-Advanced, which could double modem bill of materials
- Carrier aggregation
- Additional Wi-Fi bands

All these will add to cost, engineering complexity and power consumption just as these issues are being addressed within the first generation of LTE device profiles. Many OEMs say they will face a trade-off between supporting greater performance across a few bands, using MIMO etc., or supporting the widest range of bands, but at lower performance.

4.4.3 Cost

Handsets will still provide the bulk of mobile device volumes during this whole period, but other devices such as tablets and cloudbooks will increasingly provide the profits. There will be greater willingness to innovate and invest in other form factors apart from phones, but these will generally not have the same roaming and coverage requirements as handsets, because they will be driven by data rather than voice. Therefore there will be less pressure to support every LTE band in tablets and PCs in these categories.

Margins on smartphones will fall progressively, and so vendor success will be even more reliant on economies of scale. The trend will be to make phones that are as standardized as possible, and differentiated by superficial methods such as colour.

In section 4.8 we discuss in more detail the key cost elements of a handset which outline the total Bill of Materials for different smartphone variants/models.

4.4.4 Changing vendor profile

The commoditization of the smartphone business (i.e. smartphones move from being premium products to high volume, low margin items), and the shift of growth to emerging markets, will change the ecosystem, which will be more dominated by low cost and white label vendors, which have even greater cost constraints than the current leaders. These vendors have mainly, to date, been relevant mainly to emerging economies and the low end of the European carriers bases, rather than to LTE, but by 2018 these companies will have far higher penetration of Europe and of 4G markets, making their decisions important for EU operators.

In our survey, the differences between traditional handset vendors and the increasingly important suppliers from Taiwan and China were notable in terms of RF cost assumptions.

They are summarized here:

	Traditional vendor		Emerging vendor	
	Mass market LTE phone	Premium LTE-A phone	Mass market LTE phone	Premium LTE-A phone
Expected average BOM 2018	$50	$180	$30	$155
Target % of BOM for RF	13%	10%	16%	12%
Target RF cost	$6.5	$18	$4.8	$18.6

Table 22: BOM for traditional vendor and emerging vendor for mobile handsets

As the table shows, the new wave of LTE device suppliers will be looking to drive down costs aggressively, even at the high end, although they know that they will have to accept a higher RF percentage cost for the reasons outlined above.

In all cases, the price pressure on components which currently cost $25 to $35 in premium smartphones will be intense, and while greater scale, plus integration advances, will help, these will be offset by the rising number of band, mode and MIMO options. That will make it increasingly hard for a new or non-global band plan to be considered by mass market device makers, unless heavily supported by an operator(s).

4.5 Vendor perspective on an EU-specific 700MHz band plan:

The sections above have outlined the reasons why many vendors will be cautious about adding new LTE band plans unless they can see major economies of scale or operator support. These are general points which will apply to any new or non-global option, but there are also specific points to be made about the possibility of a European 700MHz band plan which differs from the baseline APT700, especially if Africa opts to go with the latter.

Europe is, and will remain, an important market for most smartphone vendors, but there is still considerable caution about supporting a Europe-only band plan, for two main reasons:

1. Europe represents a declining percentage of the addressable market for LTE devices, because of its own levels of saturation and the roll-out of new LTE services in major new markets e.g. parts of Africa
2. OEMs question whether 700MHz will be a priority for European operators and therefore whether it will attract the carrier support to justify a separate development, in a market which can be addressed effectively with existing bands.

These two points are detailed further in the sections below.

4.5.1 Europe as % of total market:

Europe will be a diminishing percentage of the total smartphone market as growth shifts to emerging markets and as its own LTE base saturates. Therefore there will be declining willingness by many OEMs to produce something specific for this region.

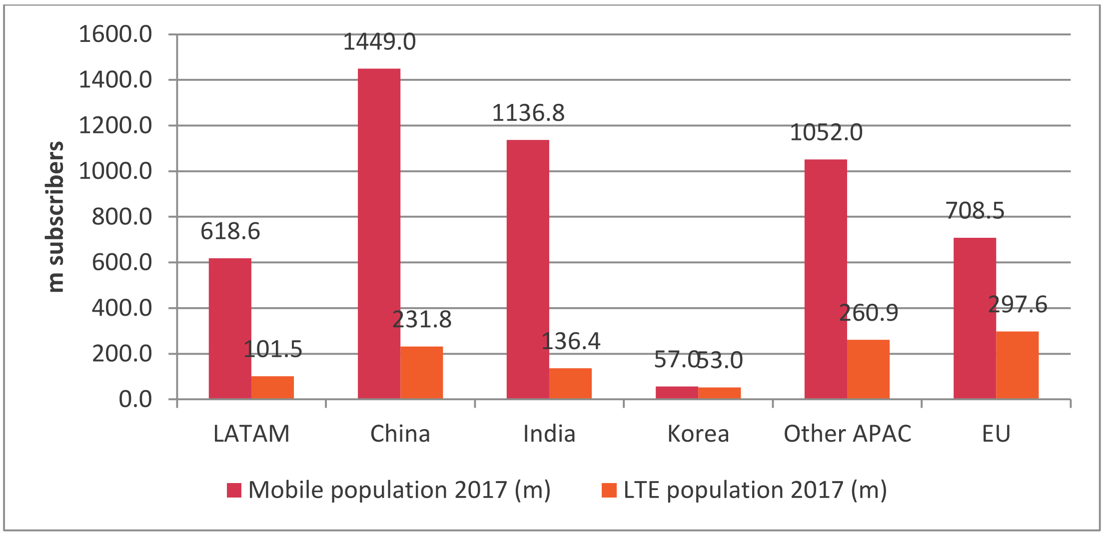

Figure 37: Mobile and LTE populations of the main regions adopting non-US 700MHz plans, forecast for 2018 (Source: Rethink Research)

As Figure 37 shows, by 2018 the EU would represent about 27% of the addressable market for non-US 700MHz LTE devices, if it were to free up 700MHz spectrum by then. That is a significant percentage, with almost 300m likely LTE users, but it will be a population largely already addressed by the vendors in older bands, and its percentage of global users will decline further after 2018.

The EU will become a smaller part of the LTE landscape as more Asian, Latin American and African operators roll out 4G, and many of these will also be running in 700MHz. In this situation, the willingness to treat Europe as a special case will be in decline because Europe will be a far smaller part of the total LTE population worldwide than it is currently.

An important factor in the OEMs' decisions will be the route taken by Africa. In many African countries, LTE will be deployed on a wide scale later than in other 700MHz regions, and so the band will have greater strategic importance to operators. In the event that Africa, or most of it, adopted APT700, Europe would be left as a far smaller part of the picture, with lower ability to drive its own ecosystem. Conversely of course, if Africa were to harmonize with a European 40MHz plan, that would be far more attractive to OEMs in terms of scale and growth potential.

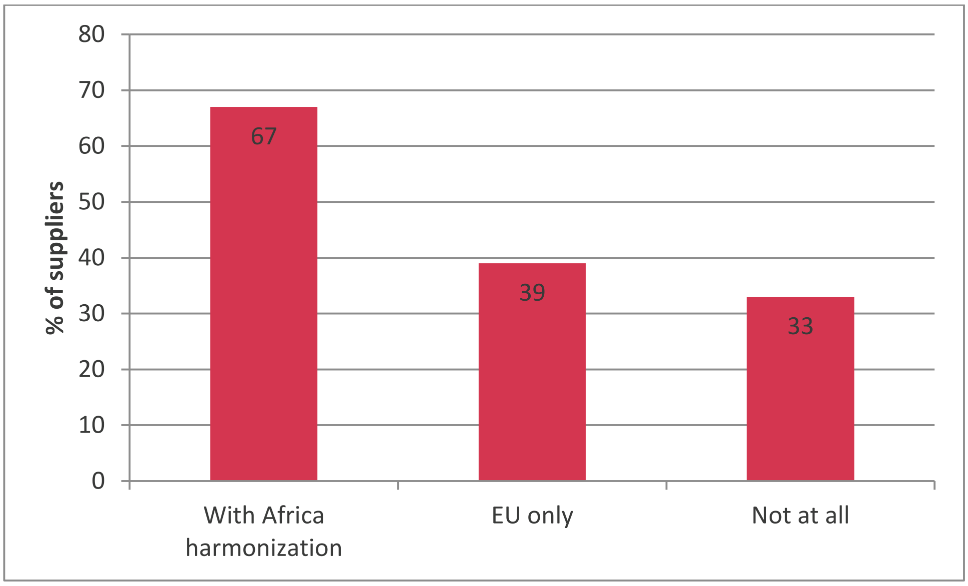

Figure 38: Percentage of those OEMs planning to support APT700 in 2018 who would support a separate band plan with 2x40MHz, across EU/Africa, or in EU alone.

This is seen in Figure 38, which shows that two-thirds of respondents would consider supporting a non-APT 2x40MHz band plan if this were adopted across much of Europe and Africa, but that figure drops to 39% for Europe alone. Many of the companies which would be prepared to customize their products for Europe are those which currently have a significant business in that region, while those which would insist on African support tend to be the newer or lower cost entrants – the companies which will drive the affordable smartphone ecosystem in the future. One-third of the respondents have little interest in a non-APT flavour of 700MHz at all.

4.5.2 700MHz as % of total European LTE base

Many OEMs believe they will be able to address a significant percentage of the European base via the established LTE bands (800MHz, 1.8GHz, 2.6GHz), and that 700MHz will be mainly an incremental band.

Studies indicate that APT700 penetration will reach up to 90% of the LTE device base in countries where that band is deployed as the first or second network (e.g. Japan), but that figure drops significantly for second wave spectrum.

Three of the respondents, unprompted, said they would be likely to add APT700 support by default to European dual- or tri-band LTE devices after 2018, if the operators were adopting the APT plan, as this would be more cost effective than customizing combinations for individual carriers. In that scenario, an ecosystem would grow up quickly without significant operator investment. The same respondents were clear, with one exception, that they would not be likely to support a non-APT flavour at all unless part-funded by an operator.

In that scenario, most of the OEMs questioned whether it would be worthwhile for operators to insist on the optimal bandwidth delivered by the 2x40MHz configuration, when the trade-off is higher device cost and lower ecosystem support. This is particularly relevant given that carriers, by 2018-20, will

- have other sources of spectrum including unlicensed (Carrier Wi-Fi etc)
- be in need of high capacity bands at higher frequencies, to enable applications like video, more than low frequency coverage bands, which will lose some of their current strategic value

4.6 Context and caveats

We are well aware that there are always issues with taking a snapshot of a community's view of a market, when we are asking them to forecast future trends. Factors which may see the real world outcome differing from the forecast include:

- Unforeseen developments in the market itself. These could include major regulatory changes or new spectrum allocations, different to those currently expected, which could alter OEMs' priorities.
- Self-interest. The view of this community is inevitably coloured by what the players would like to see happen - notably, that as few LTE band combinations prevail as possible, enhancing their economics. In reality, most players accept the situation is highly fluid, and have five-year plans which allow for a high level of flexibility to respond to real world demand. To some extent then, their forecasts of where they will prioritize device launches in 2018 reflect their ideal 'plan A', but this may change depending on operator and regulator developments.
- Operator activity. If a group of powerful operators gets behind a non-standard band plan such as a 40MHz EU700, it would have the weight to change the decisions of at least some OEMs. This is because, though Europe may represent a declining percentage of the LTE handset addressable market, its operators increasingly purchase devices on a global basis and so can influence their key suppliers accordingly. In the ODM community, those operators will increasingly include virtual players like Amazon, which are commissioning large numbers of devices of their own.

However, while the agenda of the respondents must be taken into account, we nevertheless have confidence that the prevailing view emerging from the survey has a high likelihood of translating into reality in 2018. This is because:

- While operator strategy will be key, we believe current thinking among the multinational players tends to reflect what the carriers are hearing from their device vendors. We conducted some high level interviews with the global device procurement functions of three major Europe-headquartered mobile groups and, while this was not statistically valid, it provided some useful insights. Key among them – in most cases, operators would favour a harmonized band plan, if at all achievable, in which they could acquire low cost devices. They did not see EU700MHz as sufficiently mission critical to justify a major effort to push the ecosystem towards supporting a non-standard plan, a push which would involve high levels of effort and cost.
- As the handset business consolidates into the hands of a few, those giants have considerable power to drive the ecosystem and influence operator policy. It is striking that those influential OEMs have a very united front on 700MHz, and that cohesiveness will play a major role in shaping future market development.
- The respondents shared, confidentially, a high level of detail of their 4-5 year launch plans, which are based on extensive market research and testing by the

OEMs. The resulting data goes far deeper than the vendors' high level 'public' viewpoint.

- Note: Apple, as always, was a non-respondent. The company has significant influence over operator and ecosystem choices, as its initial selection of LTE iPhone bands indicated. We assume that Apple, which is now chasing global share for the iPhone, will support all major bands by 2018. It has traditionally been very cautious about adding non-mainstream bands. By 2018, it may be that Apple has less share and influence than it currently does, but the company's decisions should be carefully watched.
- It is worth noting anecdotally that several respondents spontaneously mentioned that, when making choices between the array of extra functions they could include in a mobile device, they would currently see a Wi-Fi enhancement (eg upgrade to 11ac or, in future, perhaps 60GHz) as offering better commercial return than an additional LTE band (once a baseline two or three bands are enabled). Wi-Fi bands were not included in the survey, so we do not have hard data on this point, but it highlights how Wi-Fi will play a role in the band-support decisions of OEMs and operators.

4.7 Market engagement - Key observations

- The general view from the market analysis suggested vendors questioned the priority for a non-harmonised 700 MHz coverage band given Europe already has 800 MHz for LTE and the rest of the world do not have a sub 1 GHz band for LTE coverage. In Europe the focus would be for a >2 GHz band for high capacity according to vendor priorities.
- It is likely that the APT frequencies will become part of a default set of supported bands in future handsets because of the current band plan arrangements. Had Europe been seeking to adopt 700 MHz today vendors would be more interested in alternative arrangements.
- If Europe does adopt the APT700 frequency plan
    - The European OOB emission limits will need to be amended to meet the DTT protection requirements which would have to be subsequently incorporated into the 3GPP standards
    - Achieving European emission limits with existing filter technology is achievable so the cost impact of having the European stop band is likely to be small, particularly the RF front end module.
    - Raises the issue of the trade-off between losing and additional 2x10MHz of spectrum versus adopting a harmonized plan which would only support 2x30MHz for Europe, rather than 2x40MHz.
    - In the UK other spectrum users may wish to use harmonised spectrum for services such as public safety. This would not be possible if option 4 (2 x 40 MHz) is adopted because there would be no continuous blocks available for other uses.
- If Europe does not adopt the APT 700 frequency plan:
    - It is important for Europe to adopt the same as Africa (if this is not the same as the APT700 plan) in terms of a regional market size because by 2018 this will be one of the few growth markets
    - It would mean vendors possibly NOT including a European specific 700 MHz variant in handsets.

- Given that Europe already has 800 MHz for coverage 700 MHz might not be attractive for coverage but it could be attractive when considered to be part of a globally supported band
- By 2018 customised regional bandplan variants are likely to only be developed for high end devices (tablets, notebooks, game consoles). This will mean low end devices are unlikely to support a European specific 700 MHz handset and thus reduce its value for operators

4.8 Key cost elements in a modern UE

The RF components of a smartphone are about 10% of the total bill of materials in a dual-band LTE/triband GSM/HSPA handset. As more bands are added, the cost of the other key components is unaffected or in future some will fall, e.g. processors, and the percentage represented by RF naturally rises.

In a calculation by Vodafone on behalf of Cambridge Wireless, an LTE worldphone, covering all the 3GPP bands, would have $100 worth of components in its modem for Cat-4 LTE (i.e. supporting 150Mbps peak downlink speed), compared to $43 for a Cat-4 device supporting the three main European LTE bands plus TDD, with other costs remaining the same. Note that this exercise was somewhat hypothetical as it was conducted on a theoretical worldphone supporting every band combination, including power amplifiers, MIMO, antenna, tuners and filters which would not be commercialised.

With each additional band, the BOM rises by about $2 to $6. This becomes critical as overall handset costs fall, and in devices with low cost processors and screens, RF is the least variable cost. To illustrate the point, the table below shows comparative RF costs for two Samsung Galaxy S4 models, one supporting HSPA only and one also supporting LTE; for the iPhone 5 LTE, which has one of the lowest BOMs for a device in this premium class; and at the other end of the device spectrum, Nokia's $20 105 (non-LTE) handset (BOM calculations sourced from IHS iSuppli) [50].

This price range does not only include the filter costs, but also:

- power amplifiers (which may include both a generic multiband PC plus a region or operator specific PA for extra bands);
- envelope tracking;
- antenna switches/tuners, which get more complex with MIMO; filters.

The $6 is a maximum figure for a complex LTE-A phone with many bands and potentially 4x4 MIMO and carrier aggregation.

By contrast, in the case of a simple handset like the Nokia 105, there are only basic bands to support (2G/3G), with no advanced RF features. However, even at this low level the RF is high as a percentage of total BOM. As carriers try to squeeze LTE smartphone BOM down to $20 over time, making a low cost multiband LTE phone will be even more of a challenge.

Implementing 2-3 LTE bands is relatively simple especially if they are standard ones, but the incremental cost of adding more after that grows slightly per band, partly because of additional tuning and testing activity, partly because of less standardized PCB and antenna configurations, and need for additional functions like envelope tracking.

	Galaxy S4 HSPA	Galaxy S4 LTE	iPhone 5 LTE	Nokia 105
Total BOM (exc manufacturing)	$236	$237	$209	$13.50
RF elements	$16	$25	$34	$3
% RF	6.7%	10.5%	16%	22%

Table 23: BOM estimate breakdown across range of smartphones

In the case of the two Samsung devices, the total BOM has been reduced slightly for the LTE model by using a cheaper apps processor, but this is almost outweighed by the increase in RF costs to support just two LTE bands (other component costs have not changed significantly). The proportion of BOM taken up by RF has risen by four percentage points.

For the iPhone 5, Apple's tight control over its supply chain enabled it to spend considerably less than its rivals on most of the key components such as processor and screen ($30 less than Samsung on the latter), but the one area where it has little power to drive down cost is RF, which accounts for 16% of an otherwise thrifty BOM. Most vendors will similarly find the RF portion the hardest area to cut costs.

Generally, the cheaper the device gets, the greater proportion of BOM must go on RF, making vendors nervous about supporting additional bands, even if the incremental cost is only a few dollars. In the simple Nokia 105, RF accounts for 22% of BOM (this is an estimate as the RF is tightly integrated into a 'phone-on-a-chip' with the baseband so its costs are hard to break out accurately). The Nokia 105 is a far more simple device than current smartphones with much reduced investment in high quality displays and processing power and therefore more focus from an economics perspective is placed on RF. The economics will be in play for 4G by 2018 as these basic handset incorporate more bands to support 4G.

This study has examined the fundamental components within the UE RF front end that may impact on the implementation of a particular 700 MHz band plan. Traditionally, the quantity of components increases as additional bands are supported such as increased number of PAs, switches and filters so that more regional variants can be produced by vendors.

This process also increases the cost of producing the UE as each new component increases the unit cost. In this section we summarise the cost breakdown of a range of smartphones. This shows the Bill of Materials (BOM) for each of the components for vendors such as Samsung, Apple, HTC and Nokia.

The BOM prices for each handset has been produced by IHS iSuppli which is a company that provides market data for the bill of material for a handset teardown and provides unit prices of discrete components including, the latest released handset by top tier manufacturers. This data has enabled this report to highlight the relative costs against the total cost of producing a single handset.

4.8.1 Samsung Galaxy S4

Preliminary Samsung Galaxy S4 Teardown Estimates

Components / Hardware Elements	Samsung Galaxy S4 Korean Version SHV-E300S (LTE & HSPA+)		Samsung Galaxy S4 US AT&T Version SGH-I337 (LTE & HSPA+)	
Total BOM Cost		**$244**		**$229**
Manufacturing Cost		**$8.50**		**$8.50**
BOM + Manufacturing		**$252**		**$237**
Major Cost Drivers				
Memory - NAND Flash + DRAM	16GB eMMC + 2GB LPDDR3 + 1Gb LPDDR	$29.00	16GB eMMC + 2GB LPDDR3	$28.00
Display & Touchscreen	5" 1920x1080 Super AMOLED (441ppi), w/ Gorilla®Glass3 by Corning	$75.00	5" 1920x1080 Super AMOLED (441ppi), w/ Gorilla®Glass3 by Corning	$75.00
Processor	Samsung Exynos 5 Octa (5410)	$28.00	Qualcomm Snapdragon 600 (APQ8064T) - Quad-Core	$20.00
Camera(s)	13MP + 2MP	$18.00	13MP + 2MP	$18.00
Wireless Section - BB/RF/PA	Contains Samsung Baseband + RF Transceiver + Front End	$20.00	Contains MDM9215 + WTR1605L + Front End	$21.50
User Interface & Sensors	Contains Silicon Motion Mobile TV Soc, Broadcom NFC Controller, Atmel MCU and Sensors	$16.00	Contains Fujitsu Image Processor, Qualcomm Audio Codec, Broadcom NFC Controller, Atmel MCU and Sensors	$18.00
WLAN / BT / FM / GPS	Contains Broadcom BCM4335 + BCM47521	$8.00	Contains Broadcom BCM4335	$6.00
Power Management	Contains Samsung S2MPS11 & 60RZX6 PMICs, and Maxim MAX77803 Battery Charger IC	$9.00	Qualcomm PM8917 + PM8821 PMICs and Maxim MAX77803 Battery Charger IC	$9.00
Battery	3.8V, 2600mAh w/ NFC Antenna (Qty:2)	$10.50	3.8V, 2600mAh w/ NFC Antenna	$5.25
Mechanical / Electro-Mechanical		$22.00		$22.00
Box Contents		$8.00		$6.00

Source: IHS Inc. May 2013

Figure 39: Samsung Galaxy S4 Teardown BoM [51]

Figure 39 shows the Samsung Galaxy S4 BoM highlighting the specific costs of the RF elements. In particular it shows the difference between two regional variants (US and Korea). The cost differences in this case related to the different RF front end modules used with the AT&T version using the slightly more expensive MDM9215 + WTR1605L plus front end arrangement compared to the Korean version which uses Samsung's baseband, RF transceiver and front end. This example shows how the US version, which incorporates more bands is slightly more expensive than the Korean version with fewer bands.

Samsung Galaxy S4 SHV-E300S 32GB Key Vendors and Parts - In Descending Order of Component Value

Manufacturer	Part Number	Description
Samsung Mobile Display	AMS499QP01	Display / Touchscreen Module - 4.99" HD Super AMOLED, 1920x1080, 441ppi, Capacitive Multi-Touch
Samsung Semiconductor	Exynos 5410	Apps Processor - Exynos 5 Octa, Quad-Core ARM Cortex-A15 1.6GHz, & Quad-Core ARM Cortex-A7 1.2GHz, PoP
Samsung Semiconductor	KLMBG4GEAC-B001	Flash - eMMC NAND, 32GB, MLC
Samsung Semiconductor	K3QF2F200C-XGCE	SDRAM - Mobile DDR3, 2GB, PoP
		Primary Camera Module - Contains Sony Image Sensor, 13MP, BSI CMOS, Auto Focus Lens
Samsung Semiconductor		Baseband Processor - ARM-Core, PoP
		BT / WLAN Module - Contains Broadcom BCM4335, IEEE802.11a/b/g/n/ac, BT 4.0LE, & FM Radio
NP Tech		Battery - Li-Ion, 3.8V, 2600mAh, w/ NFC Antenna
Samsung Semiconductor		RF Transceiver
		Secondary Camera Module - Contains Samsung Image Sensor, 2MP, BSI CMOS, Fixed Lens
Triquint	TQP9058	PAM - Multi-Mode, Quad-Band GSM/EDGE, Penta-Band WCDMA/LTE
Murata	SWCGPF10	FEM - Contains Duplexer, Filter, & Antenna Switch
Samsung Semiconductor	S2MPS11	Power Management IC
Maxim	MAX77803EWJ	Battery Charger IC
Silicon Motion	FC8053	Mobile TV SoC - T-DMB/DAB
Broadcom	BCM47521	GPS / GNSS Receiver
Samsung Semiconductor		Power Management IC - for RF
Broadcom	BCM20794	NFC Controller
Samsung Semiconductor	K4X1G3333PK-XGC6	SDRAM - Mobile DDR, 1Gb, PoP
TBD		Audio Codec
Atmel	UC128L5-U	MCU
Silicon Image	Sil8240	MHL Transmitter
Sensirion AG	SHTC1	Humidity / Temperature Sensor
Bosch Sensortec	BMP182	Barometric Pressure Sensor
AKM Semiconductor	AK8963	Electronic Compass - 3-axis

Source: IHS Inc. May 2013

Figure 40: Samsung Galaxy S4 Component manufacturer [51]

Samsung Galaxy S4 (ATT 16GB) SGH-I337 Key Vendors and Parts - In Descending Order of Component Value

Manufacturer	Part Number	Description	Comment
Samsung Mobile Display	AMS499QP01	Display / Touchscreen Module - 4.99" HD Super AMOLED, 1920x1080, 441ppi, Capacitive Multi-Touch	
Qualcomm	APQ8064T	Applications Processor - Quad-Core 1.9GHz, PoP	
Samsung	K3QF2F200E-XGCB	SDRAM - Mobile DDR3, 2GB, PoP	
		Primary Camera Module - 13MP, Format, Auto Focus Lens	
Toshiba Semiconductor	THGBM5G7A4IBA4W	Flash - eMMC NAND, 16GB	
Qualcomm	MDM9215M	Baseband Processor - Multi-Mode, Multi-Band, GSM/EDGE/HSPA+/LTE, 28nm	
		BT/WLAN Module - IEEE802.11a/b/g/n/ac, Contains Broadcom BCM4335	
Qualcomm	WTR1605L	RF Transceiver - Multi-Mode, Multi-Band, CDMA/GSM/EDGE/EVDO Rev. B/HSPA+/LTE, GPS	
		Battery - Li-Ion, 3.8V, 2600mAh, 9.88Wh	
Fujitsu	MBG965H	Image Processor - ARM-Core	
		Secondary Camera Module - 2MP	
Skyworks	SKY77619-12	PAM - Multi-Mode, Quad-Band GSM/EDGE, Penta-Band HSPA+/LTE	
Murata		FEM	
Qualcomm	PM8917	Power Management IC	
MAXIM	MAX77803EWJ	Battery Charger IC	
Qualcomm	PM8821	Power Management IC	
Qualcomm	WCD9310	Audio Codec - 7 Analog Inputs, 8 Analog Outputs, 7 ADCs, 8 DACs, 6 Digital Microphone Inputs, 65nm	
Broardcom	BCM20794	NFC Controller	
ATMEL		MCU	
Silicon Image	Sil8240	HDMI Transmitter - Mobile High-Definition Link 2.0, output 1080p60Hz full HD	
Sensirion	SHTC1	Humidity / Temperature Sensor	
Bosch Sensortec	BMP182	Barometric Pressure Sensor	
Yamaha	YAS532B	Electronic Compass - 3-axis	AKM AK8963 with completely different size and package in Korean version (Flipchip-6 vs Flipchip-14)

Source: IHS Inc. May 2013

Figure 41: Samsung Galaxy S4 component vendors for AT&T operator [51]

Preliminary Samsung Galaxy S4 Virtual Teardown BOM Estimates (Pricing in U.S. Dollars)

	Samsung Galaxy S4 (HSPA Version)		Samsung Galaxy S4 (LTE Version)		Samsung Galaxy S3 (HSPA Version)	
Total BOM Cost	$236		$233		$205	
Manufacturing Cost	$8.50		$8.50		$8.00	
BOM + Manufacturing	$244		$241		$213	
Major Cost Drivers						
Memory (NAND Flash + DRAM)	16GB eMMC + 2GB LPDDR3	$28.00	16GB eMMC + 2GB LPDDR3	$28.00	16GB eMMC + 1GB LPDDR2	$29.00
Display & Touchscreen	5" 1920x1080 Super AMOLED (441ppi), w/ Gorilla®Glass3 by Corning	$75.00	5" 1920x1080 Super AMOLED (441ppi), w/ Gorilla®Glass3 by Corning	$75.00	4.8" 1280x720 Super AMOLED, w/ Gorilla®Glass2 by Corning	$65.00
Processor	Samsung Exynos 5 Octa (5410)	$30.00	Qualcomm Snapdragon 600 (APQ8064T) - Quad-Core	$20.00	Samsung Exynos 4 Quad	$17.50
Camera(s)	13MP + 2MP	$20.00	13MP + 2MP	$20.00	8MP + 1.9MP	$19.00
Wireless Section - BB/RF/PA	Possibly contains Intel PMB9820 + PMB5745 + Front End	$16.00	Possibly contains MDM9615 + WTR1605L + Front End	$25.00	Contains Intel PMB9811 + PMB5712 + Front End	$14.50
User Interface & Sensors	Contains accelerometer, RGB Light, e-compass, Gyro, Barometer, Temperature & Humidity, IR Gesture	$16.00	Contains accelerometer, RGB Light, e-compass, Gyro, Barometer, Temperature & Humidity, IR Gesture	$16.00	Contains Capella CM3663 ALS / Proximity, ST LSM330DLC Accelerometer / Gyro, AKM AK8975C e-Compass, & ST LP331AP Barometer Sensors	$12.70
WLAN / BT / FM / GPS	Possibly contains Broadcom BCM4335 + BCM47521	$9.00	Possibly contains Qualcomm Aheros WCN3680	$5.75	Contains Broadcom BCM4334 + BCM47511	$8.20
Power Management	Samsung PMIC (TBD)	$8.00	Qualcomm PMICs	$9.50	Contains Maxim PMIC	$7.00
Battery	3.8V, 2600mAh w/ NFC Antenna (TBD)	$5.60	3.8V, 2600mAh w/ NFC Antenna (TBD)	$5.60	3.8V, 2100mAh w/ NFC Antenna	$4.90
Mechanical / Electro-Mechanical		$22.00		$22.00		$21.40
Box Contents		$6.00		$6.00		$6.00

Source: IHS iSuppli Research, March 2013

Figure 42: Samsung Galaxy S4 teardown BoM for major cost drivers [52]

The Samsung Galaxy S4 smartphone teardown and BOM shows the small cost variations in components between different regions. In particular the RF components that support the multi-band and multi-technology shows only $1.50 difference between the Korean and US variants. At $20-$21.50 for the RF components compared to a total BOM of £229-$244 is a lower than 10% of the total BOM cost. In section 4.4.4 we compare the BOM between different popular smartphone handsets and below we provide some more detail on the breakdown of those component costs for other handset vendors.

4.8.2 iPhone 5

The Apple iPhone is considered to be one of the most disruptive and revolutionary consumer handheld devices to have been produced. This is based on its design focus for the consumer, user interface, operating system based on Apple OS and touch screen interaction.

The iPhone 5 is the latest version of the iPhone and supports LTE globally and in particular supports the 1800 MHz band so that it can be used by LTE networks in the UK. The following BOM breakdown captures the key components and cost drivers for the iPhone 5.

Preliminary iPhone 5 Bill of Materials and Manufacturing Cost Estimate Based on Virtual Teardown (Costs in U.S. Dollars)

		iPhone 5 Model		
Components / Hardware Elements	**iPhone 5 Hardware Comments**	**16GByte**	**32GByte**	**64GByte**
Pricing without Contract		**$649**	**$749**	**$849**
Total BOM Cost		**$199**	**$209**	**$230**
Manufacturing Cost		**$8.00**	**$8.00**	**$8.00**
BOM + Manufacturing		**$207**	**$217**	**$238**
Major Cost Drivers				
Memory				
NAND Flash		$10.40	$20.80	$41.60
DRAM	1GByte LPDDR2	$10.45	$10.45	$10.45
Display & Touchscreen		$44.00	$44.00	$44.00
Processor	A6 Processor	$17.50	$17.50	$17.50
Camera(s)	8 Megapixel + 1. 2 Megapixel	$18.00	$18.00	$18.00
Wireless Section - BB/RF/PA	Qualcomm MDM9615+RTR8600+Front End*	$34.00	$34.00	$34.00
User Interface & Sensors		$6.50	$6.50	$6.50
BT / WLAN	BTv4.0 + Dual-Band Wireless-N	$5.00	$5.00	$5.00
Power Management		$8.50	$8.50	$8.50
Battery	Assumed 1800mAh	$4.50	$4.50	$4.50
Mechanical / Electro-Mechanical		$33.00	$33.00	$33.00
Box Contents		$7.00	$7.00	$7.00

* - Assumed

Source: IHS iSuppli Research, September 2012

Figure 43: Apple iPhone 5 BoM breakdown [53]

More details on the main parts in an iPhone 5 are listed in the following table.

Apple A6 Application processor
Skyworks 77352-15 GSM/GPRS/EDGE power amplifier module
SWUA 147 228 is an RF antenna switch module
Apple 338S1077 Cirrus audio codec
Triquint 666083-1229 WCDMA / HSUPA power amplifier / duplexer module for the UMTS band
Avago AFEM-7813 dual-band LTE B1/B3 PA+FBAR duplexer module
Skyworks 77491-158 CDMA power amplifier module
Avago A5613 ACPM-5613 LTE band 13 power amplifier
Qualcomm PM8018 RF power management IC
Hynix H2JTDG2MBR 128 Gb (16 GB) NAND flash
Apple 338S1131 dialog power management IC
Apple 338S1117 Elpida memory MCP for LTE
STMicroelectronics L3G4200D (AGD5/2235/G8SBI)
Murata 339S0171 Wi-Fi module
STMicroelectronics LIS331DLH (2233/DSH/GFGHA) three-axis linear accelerometer
Texas Instruments 27C245I touch screen SoC
Broadcom BCM5976 touchscreen controller
Qualcomm MDM9615M LTE modem
RTR8600 Multi-band/mode RF transceiver

Table 24: iPhone 5 list of major components

The above table illustrates the number of different duplexer, PA and switch modules required to support each of the technologies and multiple bands in a single handset.

The following table shows the Apple iPhone 5 BOM across the different available models with the main cost variant being the size of the available memory. The RF component costs remain the same across each model.

IHS iSuppli Table: Preliminary iPhone 5 vs. iPhone 4S Cost Estimates

	Apple iPhone 5 (Pricing as of Sept, 2012)				Apple iPhone 4S (Pricing as of Oct, 2011)			
Components / Hardware Elements	iPhone 5 Hardware Comments	16GB3	32GB4	64GB5	iPhone 4S Hardware Comments	16GB32	32GB43	64GB54
Pricing without Contract		$649	$749	$849		$649	$749	$849
Implied Margin		68%	71%	72%		70%	71%	70%
Total BOM Cost		$199	$209	$230		$188	$207	$245
Manufacturing Cost		$8.00	$8.00	$8.00		$8.00	$8.00	$8.00
BOM + Manufacturing		$207	$217	$238		$196	$215	$253
Major Cost Drivers								
Memory								
NAND Flash		$10.40	$20.80	$41.60		$19.20	$38.40	$76.80
DRAM	1GB LPDDR2	$10.45	$10.45	$10.45	512MB LPDDR2	$9.10	$9.10	$9.10
Display & Touchscreen	4" Retina Display w/ In-Cell Touch	$44.00	$44.00	$44.00	3.5" Retina Display w/ Touch	$37.00	$37.00	$37.00
Processor	A6 Processor	$17.50	$17.50	$17.50	A5 Processor	$15.00	$15.00	$15.00
Camera(s)	8MP + 1.2MP	$18.00	$18.00	$18.00	8MP + VGA	$17.60	$17.60	$17.60
Wireless Section - BB/RF/PA	Qualcomm MDM9615M+RTR8600 +Front End	$34.00	$34.00	$34.00	Qualcomm MDM6610+RTR8605 +Front End	$23.50	$23.50	$23.50
User Interface & Sensors		$6.50	$6.50	$6.50		$6.85	$6.85	$6.85
WLAN / BT / FM / GPS	Murata Dual-Band Wireless-N Module	$5.00	$5.00	$5.00	Murata Single-Band Wireless-N Module	$6.50	$6.50	$6.50
Power Management	Dialog + Qualcomm	$8.50	$8.50	$8.50	Dialog + Qualcomm	$7.20	$7.20	$7.20
Battery	3.8V ~1400mAh	$4.50	$4.50	$4.50	3.7V ~1400mAh	$5.90	$5.90	$5.90
Mechanical / Electro-Mechanical		$33.00	$33.00	$33.00		$33.00	$33.00	$33.00
Box Contents		$7.00	$7.00	$7.00		$7.00	$7.00	$7.00

Source: IHS iSuppli Research, September 2012

Figure 44: iPhone 5 BoM across two handset variants iPhone 4 and iPhone 5 [54]

4.8.3 Nokia Lumia 900

The Nokia Lumia 900 recently entered the smartphone market around June 2012 and was Nokia's flagship LTE handset. The Lumia uses Microsoft Windows operating system which is the third most popular phone operating system.

Preliminary Analysis - And Comparison With Samsung Galaxy SII Skyrocket

Components / Hardware Elements	Nokia Lumia 900	Samsung SII Skyrocket
Retail Pricing (As of April 2012)	$449.99	$549.99
Total BOM Cost	$209.00	$235.50
Manufacturing Cost	$8.00	$8.00
BOM + Manufacturing	$217.00	$243.50
Major Cost Drivers		
Memory	$27.00	$32.00
Display & Touchscreen	$58.00	$64.00
Processor	$17.00	$22.00
Camera(s)	$18.00	$20.00
Wireless Section - BB/RF/PA	$38.00	$37.00
User Interface & Sensors & Combo Module (WLAN/BT/FM)	$14.00	$16.50
Power Management	$9.00	$11.00
Battery	$4.50	$5.00
Mechanical / Electro-Mechanical / Other	$18.00	$22.00
Box Contents	$5.50	$6.00

Source: IHS iSuppli Research, April 2012

Figure 45: Nokia Lumia breakdown BoM Source: [50]

5. Response to Ofcom's specific questions

In this chapter we address explicitly each of the questions that were posed by Ofcom to determine the main issues of handset vendors supporting a European 700 MHz band against different band plan options. The broad areas of scope included:

Implementation considerations relating to:

- Adjacent band coexistence
- In band performance

Support for 700 MHz in multi-band terminals

- Dual duplexer implementation
- Impact on performance of terminals
- Financial cost of adding filters

In advance of responding to these questions we distil and narrow down the bandplan options based on the technical analysis of this study. Therefore, we summarise the issues against each of the options to be analysed further and address the questions in the following sections below.

Band plan option	Available spectrum	Degree of harmonisation	Cost difference from today	Recommendation
1 – 703-733 MHz paired with 758 – 788 MHz	2 x 30 MHz	Full harmonisation with APT700 lower duplex	Need for inclusion of filters that achieve 45 dB rejection into DTT	This bandplan is a viable option based on the achievable frequency separation, the use of current filter technology and ability to achieve 45 dB attenuation to protect DTT services. This will also provide harmonisation with APT700 frequencies
2 - 698-733 MHz paired with 753 – 788 MHz	2 x 35 MHz	Partial harmonisation with APT700 lower duplex (703 MHz- 5 MHz)	Depends on number of cascaded filters needed to meet 45 dB rejection into DTT	This is not a viable option due to the small transition band and filter implementation cost and complexities
3 - -693 – 733 MHz paired with 748 – 788 MHz	2 x 40 MHz	Partial harmonisation with APT700 lower duplex	See recommendation	This is not a viable option as it overlaps with DTT and so is not

Band plan option	Available spectrum	Degree of harmonisation	Cost difference from today	Recommendation
		(703MHz – 10 MHz)		considered further in the report
4 - 703-743 MHz paired with 751 – 791 MHz	2 x 40 MHz	Partial harmonisation with APT700 lower duplex except for an addition 10 MHz above 733 MHz	Need for a dual duplexer and for inclusion of filters that achieve 45 dB rejection into DTT	This bandplan is a viable option and is attractive as it allows 2 x 40 MHz thus maximising spectrum availability. This overlaps the APT 700 band plan with the lower duplex part in principal could support global roaming
5 - 701-741 MHz paired with 751 – 791 MHz	2 x 40 MHz	Partial harmonisation with APT700 lower duplex (703 MHz- 2 MHz)	Need for FBAR filter and dual duplexer to achieve 45 dB rejection with on 7 MHz frequency separation	This is the costliest implementation as it requires FBAR filter technology but is feasible and uses the whole 2 x 40 MHz bandwidth effectively.
6 - 703- 743 MHz paired with 748 – 788 MHz	2 x 40 MHz	Partial harmonisation with APT700 lower duplex except for an addition 10 MHz above 733 MHz	Need dual duplexer (See recommendation)	This is not a viable option due to switching complexity which would limit harmonisation achievable. 5 MHz duplex gap is not sufficient for the BS to isolate the TX/RX paths

Table 25: Summary matrix of band plan options

The study questions are represented below with detailed responses associated with each.

5.1 Q1: Adjacent band coexistence

1	What is the level of unwanted emissions into DTT channel 48 that can realistically be achieved from a mobile device, with sufficient confidence to be built into a harmonised standard? The answer should assume the mobile transmit band starting at: (a) 703 MHz (9 MHz frequency separation), and (b) the other frequencies currently proposed in the ITU (see Annex 1). The results should be presented in graphical form, showing emission level vs relative cost.

In chapter 2 and in section 3.3.4 we discussed the level of unwanted emissions into DTT channel 48 from UEs that could potentially create detrimental effects to users in the service area. The research conducted to address this question required the examination of the possible levels of attenuation that could be achieved by implementing the latest filter, PA and other methods (such as envelope tracking) to protect DTT services.

We found that the limits proposed by the UK/CEPT can be achieved using current filter technology so long as there is a 9 MHz frequency separation i.e. stopband starting at 703 MHz with 2 out of 4 filter vendors being able to achieve this with current technology SAW/BAW and a space of 6 MHz can be achieved using FBAR technology.

	Insertion loss Max	Atteuation at 694MHz (dB)
Vendor 1	3	45
Vendor 2	3	45
Vendor 3	3	30
Vendor 4	3	5-15

Figure 46: Summary of vendors' ability to achieve attenuation at 694 MHz

This data is reasonably consistent with preliminary simulation data for the band 28 lower duplex filter presented in TR 36.820 table 8.2.1-1, last column repeated below.

Filter data from different UE vendors for both dual duplexer configurations are shown in Table 8.1.1-1 and Table 8.1.1-2 considering protection of adjacent services (TV @694 MHz following AWG recommendation, -34dBm/MHz) and own DL operating band as well as rejection against UL blockers in its own band. This data is preliminary and just indicate the performance difference between the two possible dual duplexers.

Table 8.1.1-1. Simulation results for the lower filter

Vendor	pass-band	Tx IL (min)	Rx IL (min)	Rx Iso (min)	Tx Iso (min)	Tx Att (min) @694MHz
1	30 MHz	3.8 dB	3.7 dB	42 dB	55 dB	35 dB
	32.5 MHz	5.0 dB	4.5 dB	42 dB	55 dB	35 dB
2	30 MHz	5.0 dB	5.0 dB	40 dB	51 dB	15 dB
	32.5 MHz	7.5 dB	5.0 dB	40 dB	53 dB	15 dB
3	30 MHz	3.5 dB	3.5 dB	47 dB	55 dB	23 dB
	32.5 MHz	4.0 dB	3.5 dB	47 dB	50 dB	23 dB

Figure 47: Extract from 3GPP TR36.820 band 28 Lower Duplex. Table 8.1.1-1 Simulation results for lower filter

Achieving sufficient protection to DTT services starts to become challenging for filters with wider bandwidths (>30 MHz). Filters that are in production and those under development that have specified rejection in the DTT band up to 45 dB are typically designed for 30 MHz bandwidths or lower resulting in the need for a dual duplexer in the case of option 4, 5 and 6.

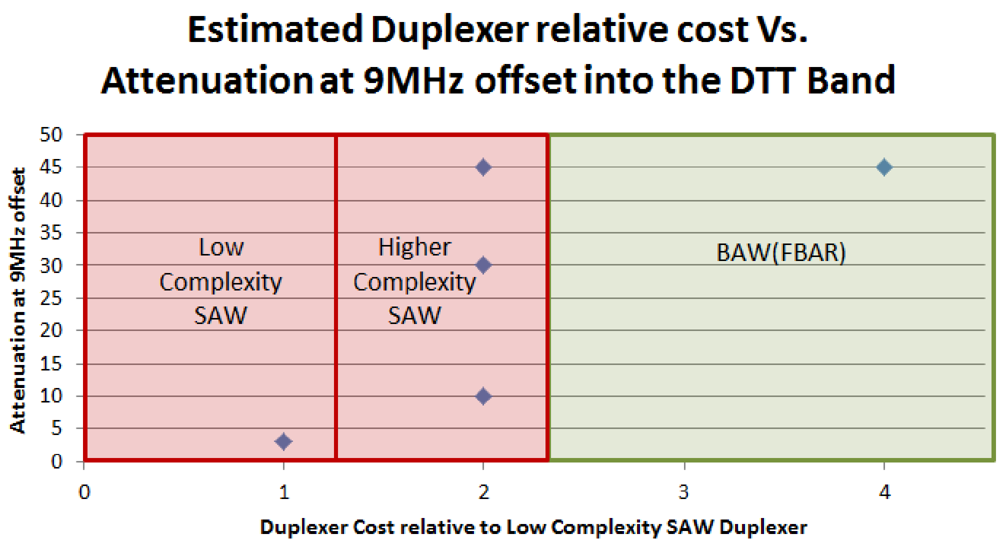

Figure 48: Estimated Duplexer cost Vs. Attenuation at 9MHz offset into the DTT Band

Figure 48 shows the relative cost points of the different duplexer realisations to achieve the associated attenuation at 9 MHz offset (option 1, 4 and 6). Low complexity SAWs will not be able to achieve the required 45dB attenuation. Some higher complexity SAW realisations will be able to achieve the required attenuation in CH48 but at an estimated double the cost of a low complexity SAW. BAW filters can achieve the required attenuation at a price which is estimated to be about 4 times the price of a low complexity SAW.

5.2 Q2: In-band performance

2	On the basis of current filter performance and trends in development of filtering technology, provide an assessment of the trade-offs in the implementation of the duplexer(s) and filtering in a 700 MHz mobile terminal for the different European band plan options. This should address the following competing objectives: • Minimising unwanted emissions below 694 MHz (for coexistence with digital TV) • Maximising the efficient use of spectrum within the 700 MHz band for mobile broadband • Maintaining in-band performance and filtering across the centre duplex gap • Minimising implementation costs, including considerations on single duplexer vs dual duplexer in a multi-band terminal • Full or partial commonality with channelling arrangements in other regions of the world Results are to be provided as a matrix of the costs of implementing the 700 MHz band in a mobile terminal on the basis of: a) prioritising individual objectives from the above list, and b) prioritising combinations of the above objectives for the options for channelling arrangements that we have outlined in the background of this Appendix. The output should focus on cases where minimised unwanted emission limits below 694 MHz for coexistence with digital TV is a priority.

We have discussed in section 3.1 the capabilities and characteristics of the latest filter technologies and performance. We engaged with a number of filter manufacturers that supply the mobile handset industry and have also developed (and developing) solutions to support the 700 MHz band to be added to new handsets.

In section 3.1 we established representative requirements for filter in-band performance in order to assess the specific performance characteristics therefore we set parameter values according to industry standards. For example, the TX isolation was chosen to be 45dB and the RX isolation was chosen to be 43dB. A guideline max insertion loss was chosen to be 3dB.These specifications are typical for current UE designs. A certain amount of attenuation will also be required in band 20 to protect from any emission from the 700 MHz band. However this is a downlink band and therefore we assume a relatively low attenuation will be required.

In addition to these basic requirements we add the rejection specification of 45dB in the DTT band. The total set of requirements are captured in a filter template format for discussion with filter manufacturers. Templates were generated for all of the options considered. The same basic in-band requirements were applied to all options. An example of the template for option 1 is shown below in Figure 49.

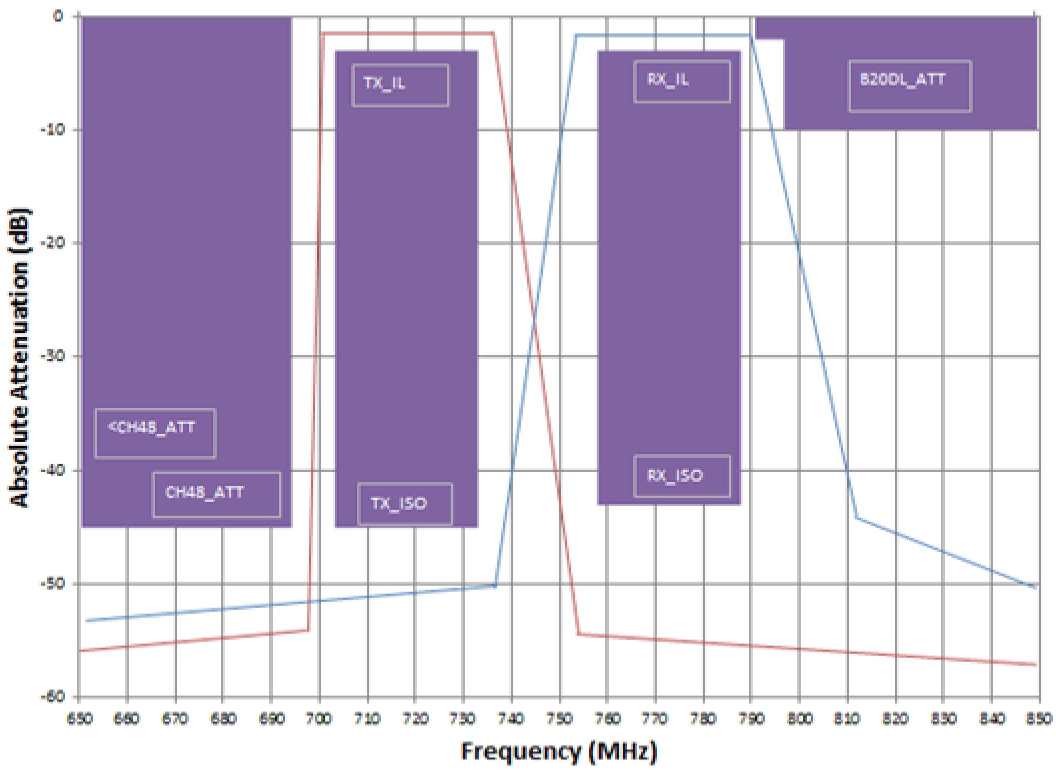

Figure 49: Option 1 Filter Template (In-band Performance)

The need for a dual duplexer is dictated by the size of the fractional bandwidth and the centre frequency (the size of the passband is the bandwidth divided by the centre frequency). The most common trade-off is when attenuation performance decreases as the passband bandwidth increases as shown in section 3.8.1. This is mainly due to the physical characteristics and constraints of the filter being able to support both features to a sufficient level that is designed to ensure in band performance. Historically, filters in handsets are designed to ensure adjacent channel interference is maintained to protect the same service rather than to protect different adjacent services such as DTT services.

Commonality with all other global FDD bands was studied. The only practical commonality possibility is with band 28. The US bands are too fragmented to achieve a commonality in both duplex directions. Therefore we have only consider commonality with the APT 700 in the assessment below.

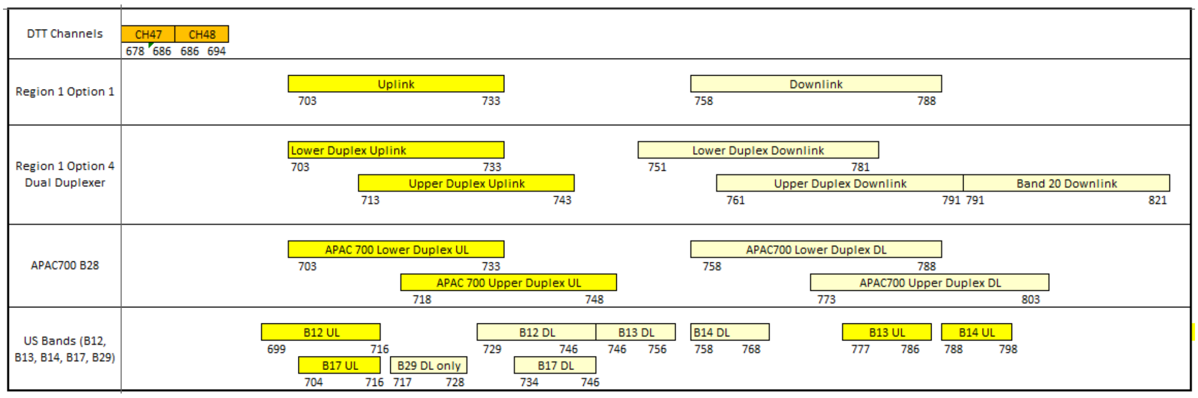

Figure 50: R1 700 Band Option 1 and 4 compared to APAC700 and US Bands

	Option 1 (SAW	Option 1 (FBAR)	Option 2 (FBAR APT+5MHz)	Option 3 (overlaps DTT)	Option 4 (FBAR Dual Duplexer)	Option 4 (Dual Duplexer)	Option 5 (SAW, not realisable	Option 5 (FBAR Dual duplexer)	Option 6 (SAW Dual Duplexer)	Option 6 (FBAR Dual Duplexer)
Bandwidth	2x30	2x30	2x35	2x35	2x40	2x40	2x40	2x40	2x40	2x40
Commonality with band 28 lower duplex	2x30	2x30	2x30	2 x 30	2x30	2x30	2x30	2x30	2x30	2x30
Re-use of band 28 lower duplex filter	Yes	Yes	No	No	No	No	No	No	No	No
Achievable suppression	5 to 45	45	No	No	5 to 45	45	No	45	5 to 45	45

Table 26: Band Plan Options Performance Matrix

Assuming that achieving the conservative protection requirements of DTT consistent with the UK submission to CEPT [4]. Table 26 provides an assessment of the overall performance of the feasible options in each band using different technologies. From this we can deduce:

- Lowest cost option: Lowest cost option would be a SAW implementation of Bandplan Option 1. This would result in use of 2x30 MHz, and be compatible with the APT bandplan;
- Maximally harmonised solution: If bandplan option 1 was used and if handsets for use in both APT and EU regions would use the same filter components then the marginal cost of adopting a harmonised bandplan would be zero. This would require revision and adoption of 3GPP specifications in order for the EU700

stopband limits to be adopted for use in Asia[45]; Note – The spectrum will not be available in Europe until 2018

- Highest frequency utilisation: Options 4-6 allow support of 2x40 MHz of spectrum and all of them overlap with the APT700 bandplan allowing access to 2x30 MHz of the APT700 Bandplan. Handset implementations would need to adjust their switching network to use appropriate duplex offsets which may not readily align with options 4-6 – but this is achievable. The cheapest options which offers this functionality are Options 4 or 6 with existing SAW technology.
- Note that if Option 1 cost could be reduced if band 28 is implemented with emissions meeting the European requirements.

[4] It is not clear that low price APT700 region would readily accept using more restricted EU700 stopband limits to reduce the cost of low-end phones that may never need to roam into Europe.
[5] EU700 Bandplan should be agreed at WRC2015, which would provide sufficient time for inclusion in a 3GPP release ready for use in 2018.

5.3 Q3: Dual duplexer implementation

3	How does dual duplexer implementation of a band (which might be required for a 2x40 MHz channelling arrangement in the 700 MHz band) impact the number of supported bands in a mobile terminal?

We have noted in our analysis that each duplexer incorporates the same amount of complexity as adding a new band to a multi-band phone. In addition, if we assume there are enough ports in the baseband processor which can also be expanded by using switches as shown in Figure 12 in section 3.

Modern phones, particularly smartphones also support other radio frequency bands such as dual band Wi-Fi / Bluetooth (2.4 and 5 GHz) and also GPS.

We also note that there is a limit to the number of bands supported across mobile technologies currently being implemented into mobile terminals. An example of the number of bands a high end smartphone can support is shown below:

- GSM = 3
- WCDMA = 4
- LTE = Up to 13 for the Apple iPhone 5S US variant [32]

The choice of which bands to support is up to the vendor and which market it intends to support. We provide a full analysis of the addressable market for 700 MHz in section 4.

The requirement for a dual duplexer to support a particular band arrangement is influenced by:

- The physical characteristics of the filter
- The size of the pass band
- The centre frequency
- Cost
- OOB performance
- Insertion loss

These factors are all considered when designing an appropriate filter to support a particular band. We address the study question in terms of how a dual duplexer might impact the number of supported bands in a mobile terminal in two ways:

1. Cost
2. Performance

Cost

The cost implications of incorporating a dual duplexer in a mobile terminal are comparable to the cost of adding a new band. For example, if a vendor opted to implement a dual duplexer within its handset design the cost would be the same as if the vendor wanted to implement a new band.

We found from our research with filter vendors that it is approximately the same price as a higher complexity SAW duplexer to add a stand-alone PA for a new LTE frequency band.

Performance

The practical limitations of adding more functionality to handset impacts the physical size and available space on the silicon. Adding a dual duplexer will increase the size of filter and thus take up more space on the silicon. There are however, novel techniques that allow vendors to realise the handset RF front end.

Packaging can all be integrated in 1 module such as Qualcomm RF360 and to a lesser extent the Skyworks SkyOne. This approach is considered to be more expensive and potentially open to 'Margin Stacking' as vendors will have to source some of the component parts externally. Although overall size is reduced there may be cases where less integrated solutions may be easier to fit into the available space in a handset.

The less integrated solutions could be vertically 'sliced' on a technology basis or horizontally 'sliced' on a band basis. There are advantages to integrating the filters with the PAs (PAD) so horizontal slicing can be a good solution. This is the approach adopted by Apple. Avago and TriQuint manufacture both Power Amplifier and Filters. Both of these companies offer PAD solutions.

In terms of the ability to support multiple bands; single band, Dual Band and Quad band PAD options are now available thus reducing the available space in a handset. 6 band support UE implementations are possible and will soon be available for implementation in handsets.

Therefore, with developments in current technology both integrated and non-integrated designs would be a practical solution to readily enable the inclusion of a dual duplexer in a multi-band environment into a single handset. This assumes sufficient ports on the RFIC and available ports on switches. Otherwise, additional ports will be needed on both the RFIC and switches thus increasing the required space and therefore cost. However, the cost drivers will encourage the use of only the most attractive bands in future lower end phones.

5.4 Q4: Impact to the performance of a terminal in existing bands

4 Would there be any impact on the performance of a terminal in existing bands (e.g. 800 MHz, 900 MHz) if the European channelling arrangement for 700 MHz did not align with the Asia-Pacific channelling arrangement, and therefore had to be implemented separately in that terminal.

- Considering all of the above, what are your conclusions on the different levels of support that we should expect for (a) a new 700 MHz Region 1 band plan or (b) adoption of the Asia-Pacific* 700 MHz band plan?

* Note that the current terminal specification for the Asia-Pacific 700 MHz band permits

significantly higher limits on unwanted emissions below 694 MHz than we would require for coexistence DTT use of channel 48 in Europe. Therefore, if Europe decided to use the Asia-Pacific channelling arrangement, there would still be a need to address emission limits in the specifications and in terminal implementation.

In our analysis in section 3 we discuss in detail the impact of performance of the handset due to implementing harder (relative to the 3GPP specification limits) out of band suppression levels, the possibility of supporting a mix of transition bandwidths (4, 5 and 9 MHz) and the possibility of including a dual duplexer.

Adding 700 MHz capability to a multi-band handset is unlikely to impact on performance. This is because the isolation provided by high isolation (30 dB) low loss (0.45 dB with a Single Pole Six throw (SP-6T) and 0.50 dB for SP-8T) would isolate the existing bands from any additional band. NB Only one band is assumed to be active at any one time.

We note that intermodulation products could be produced if GSM and LTE were operating simultaneously i.e. voice and data channels. Intermodulation could also occur if carrier aggregation was implemented and the handset was receiving on multiple bands.

In terms of the study conclusions on the different levels of support that could be expected from vendors, we draw upon our findings from the market analysis in which we engaged with over 20 vendors/operators from across the industry:

- We note that industry group Digital Europe and one of the filter manufacturers support the adoption of the APT700 as band for use across Europe based mainly on the global harmonisation benefits
- The majority of the handset makers, predictably, support the adoption of APT700, which would improve their economics. Less than half of OEMs would consider supporting an EU-only band. Vendors with a European focus would still support the band, but potentially in only a few handset models. Consumers would have a smaller choice of handsets than those in other regions.

5.5 Q5: Financial cost against different 700 MHz band plan options

5 What is the per handset financial cost of adding filters to mobile terminals and how does this differ for different 700 MHz band plan options?

- Are there significant research and development costs in developing support for the 700 MHz band in mobile terminals?
- Is there an opportunity cost in supporting 700 MHz in mobile terminals e.g. will work be diverted from development of support for other mobile bands?
- Are there significant economies of scale in these costs e.g. would partial or full harmonization with the APT band plan reduce costs?

The cost to handset vendors of adding a new band to a UE is that of a higher complexity SAW or BAW filter and a SAW diversity receive filter, assuming that sufficient RF ports are available on the RFIC, sufficient switch ports are available and that an existing power amplifier can support the new band. If a new power amplifier is needed, this would add an amount equivalent to a higher complexity SAW Duplexer for a single PA.

From an R&D standpoint components such as switches and power amplifiers are already available to support the 700MHz band. An example is the TriquintTQM700013Band 13 LTE power amplifier Module. Therefore, no additional R&D costs will be spent on developing PAs in handsets.

This means the duplexers and RX filters are the components that will need to be developed for the new European 700 MHz band but these are within the scope of capability of several manufacturers using current technology. The likely spend in areas such as design time (including simulation), test wafer, component prototype, testing, heat cycling etc will be R&D spend but unlikely to be significant relative to adding any other new component.

Regarding the mobile terminal development, if band 28 is already supported with a dual duplex implementation and the 30MHz option 1 is chosen then the R&D costs are not expected to be significant. All filter vendors have informed us that EU DTT protection limits can be met, however only two of them have products that do meet the limits.

Handset vendors may be concerned about the total BoM, rather than the minor component costs of an additional filter. For a high end device that supports multiple bands the price of a filter is negligible compared to the additional co-existence verification with other bands i.e. integration and testing that is associated with adding a new band to a handset. Handset vendors would likely see this as a market decision. That decision will not be a simple one of volume and retail price but will be influenced by operator commitment – how far an operator will pay a premium, or commit to marketing activity, or to subsidies, to secure a 700MHz device. This is a reason many operators round Europe have expressed support for a harmonized bandplan so they can access handsets that are already developed.

For example for a large global vendor, the European market may be deemed a relatively small opportunity and if combined with additional cost this raises the question whether there will be a sufficient return on investment. For OEMs for which Europe is not their primary target, they may feel able to address the EU by supporting the existing band combinations (800/1800/2600), with incremental sales from adding 700MHz being insufficient to justify any additional cost or operator testing effort.

From the perspective of a large handset vendor, adding a new band does not present an opportunity cost. This is because the large investment budgets would be focussed on opportunity where the largest return is likely to be realised, and thus becomes a commercial decision. From the market survey the issue is not what the opportunity cost of developing an EU700 variant would be. It is rather whether there is sufficient market opportunity to support an EU specific bandplan given the existing sub 1 GHz bands.

In terms of full or partial harmonisation, only full harmonisation would achieve economies of scale for EU 700 handsets. If APAC region could adopt use of filters complying with more stringent EU limits and the option 1 frequency band plan is adopted in Europe then this could create a new harmonised, global mobile band (except US) using existing technology and small, if any, additional cost.

Any deviation from full harmonisation is likely to require EU specific handset variants and therefore Europe adopting a 2 x 40 MHz variant to increase the spectrum utilisation. This would have a small additional cost per handset. Even low additional cost amounts (that of a high complexity SAW filter) are a consideration for phones with BOM of $20 or less by 2018. Adding any cost means the 700MHz option could go unsupported in mass market devices and be a premium option only. However, this would result in a handset likely to have two dual duplexers in the 700 MHz band (we expect APAC to be a standard band in most handsets by 2018). The European variant would work in Asia but the Asian variant would exceed the DTT protection limits and thus not be allowed. Additionally, the European variant could suffer constraints on what additional bands may be supported.

If Europe decides to adopt a bandplan that is partially harmonised with the APT700 band then it is possible the resulting 700 MHz band in Europe may not be attractive to European operators, especially if they perceive that they have sufficient sub 1 GHz spectrum already. However, Ofcom, Real Wireless and others have illustrated the potential growth in demand for mobile traffic in future. This demand is also likely to be consumed in locations where 700 MHz would be of much benefit i.e. deep indoors and rural areas. Therefore, we note that there will be a continued need for more spectrum and thus even if a European ecosystem emerges the spectrum will be of some value to European operators based on the expected growth in mobile traffic demand. The perceived value of this spectrum and availability of handsets is likely to be increased if any European variant is aligned with Africa.

6. Appendix A: Acronyms

ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
A-MPR	Additional Maximum Power Reduction
AWGN	Additive White Gaussian Noise
APT	Asia Pacific Telecommunity
AWS	Advanced Wireless Services
BAW	Bulk Acoustic Wave
BOM	Bill of Materials
BS	Base Station
BW	Bandwidth
CA	Carrier Aggregation
CDMA	Code Division Multiple Access
CMOS	Complementary Metal-Oxide Semiconductor
DCS	Digital Cellular Service
DL	Downlink
DTT	Digital Terrestrial Television
EDGE	Enhanced Data Rates for GSM Evolution
ET	Envelope Tracking
E-UTRA	Evolved UMTS Terrestrial Radio Access
EUTRAN	Evolved UMTS Terrestrial Radio Access Network
EVM	Error Vector Magnitude
FBAR	Film Bulk acoustic Resonator
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FEM	Front End Module
GSM	Global Standard for Mobile Communications
LTE	Long Term Evolution
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MOP	Maximum Output Power
MPR	Maximum Power Reduction
MSD	Maximum Sensitivity Degradation
OEM	Original Equipment Manufacturer
OOB	Out-of-band
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PCC	Primary Component Carrier
PCS	Personal Communications Service
P-MPR	Power Management Maximum Power Reduction
POP	Package-on-Package
RE	Resource Element
REFSENS	Reference Sensitivity power level
RFIC	Radio Frequency Integrated Circuit
r.m.s	Root Mean Square
RX	Receive
SAW	Surface Acoustic Wave
SINR	Signal-to-Interference-and-Noise Ratio
SMR-BAW	Solidly-Mounted Resonator Bulk Acoustic Wave

SNR	Signal-to-Noise Ratio
TDD	Time Division Duplex
TX	Transmit
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRA	UMTS Terrestrial Radio Access
UTRAN	UMTS Terrestrial Radio Access Network
WCDMA	Wideband-Code Division Multiple Access

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