GSMA Response to the Ofcom (UK) consultation on the use of Digital Dividend Review (6th June 2008)

The GSMA welcomes the chance to input to this important consultation on use of UHF spectrum. The GSMA has been undertaking some research regarding the practical frequency flexibility that is possible for mobile 3G terminals, and the impact this might have on their cost and performance. That is to what extent the frequency bands of various markets must align, to allow economies of scale to drive down terminal costs and improve performance. This report by RTT is available on their website[1].

However we believe that this work is important regarding the UK specific proposals. We have therefore requested that RTT use the general Europe wide findings they discussed in their report to look at the UK. This UK specific analysis document is attached to this response[2] and we would ask that Ofcom consider it's findings.

Specifically that : "***This study shows that it unlikely that special to purpose half duplex FDD devices will be produced for the European market. It is even more unlikely that country specific variants including products for the UK market will be supported.***

We therefore conclude that the spectrum being released by Ofcom is unlikely to be supported by mass market terminals. "

It also notes that ***: "This reluctance can be simply explained. Europe presently constitutes 24% of the global handset market by volume. By 2012 this share will have reduced to 12%. The UK is a small percentage of this European market. The UK today accounts for approximately 2% of the world market. By 2012 this will have reduced to 1%. "***

This implies that failure to harmonise frequency bands with other European countries and along internationally agreed lines (such as the CEPT and the ITU/ WRC) could lead to UK consumers either :

1. Not having access to mass market mobile services using this spectrum; or
2. That the cost of such services will be significantly higher than they otherwise would have been.

Such an outcome should be considered in any regulatory impact analysis, and weighed against issues such as the value of regional television broadcasting, for example.

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[1] http://www.rttonline.com/Research/V21 Halfduplexstudyfinaljuly08 .pdf
[2] Annex 1

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GSMA Association

August 2008

www.GSMWorld.com

About the GSM Association

Founded in 1987, The GSM Association (GSMA) is a global trade association representing more than 750 GSM mobile phone operators across 218 territories and countries of the world. In addition, more than 180 manufacturers and suppliers support the Association's initiatives as associate members.

The primary goals of the GSMA are to ensure mobile phones and wireless services work globally and are easily accessible, enhancing their value to individual customers and national economies, while creating new business opportunities for operators and their suppliers. The Association's members serve more than 3 billion customers.

The GSMA believe that the promotion of open, competitive market conditions is fundamental to extending the benefits of mobile communications to all, from the most developed Western European and North American markets to remote areas in Developing Countries. Mobile has a critical role to play in improving health, wealth, education and social mobility. To this end the GSMA launched its Emerging Market Handset Programme to produce sub $30 (US) GSM handsets.

The GSMA also hopes to replicate this GSM handset program success for 3GSM enabled handsets. This initiative is called "3G for All". Under this initiative, which builds on the success of the GSMA's Emerging Market Handset programme, mobile phone suppliers will compete to design a 3G handset that meets the operators' common requirements. Twelve operators will evaluate and score the proposals submitted by handset vendors against the following criteria - functionality, usability, logistics, market acceptance, target price, service and support, strategic commitment and form factor. The GSMA hopes to announce the winner of this selection process at the 3GSM World Congress at Barcelona, in February 2007[3].

[3] For more details see: http://www.gsmworld.com/news/press_2006/press06_47.shtml

Annex 1

RTT Study on UK issues

Ofcom Consultation, Digital Dividend Review: 550-630 MHz and 790-854 MHz.

Compiled, researched and prepared by RTT with market data from The Mobile World.

August 2008

1) Executive summary

RTT were commissioned by the GSMA to study whether half duplex FDD provides a technically and commercially viable and/or attractive solution for the Digital Dividend spectrum. .

A number of the industry inputs in to the study were considered to be directly relevant to the Ofcom DDR consultation process.

One of the questions we were asked is whether half duplex FDD would allow for a 'one size fits all' approach to producing handsets for the European market. The comments gathered and the technical analysis for the study suggest unambiguously that this is not the case either for the European market taken as a whole and/or for individual countries within Europe wishing to introduce band plans that are sufficiently different to be problematic in terms of RF design, RF component availability and network deployment. The UK is one example.

The consensus from respondents from the RF component community, transceiver and handset vendors that half duplex FDD LTE at 800 MHz will be hard to justify unless more universally adopted in other LTE bands. However there is little appetite within the industry for a more generic implementation of half duplex FDD. The perception is that any cost and performance benefits would be hard to achieve and would be unlikely to realise an acceptable return on the R and D and production investment needed.

This reluctance can be simply explained. Europe presently constitutes 24% of the global handset market by volume. By 2012 this share will have reduced to 12%. The UK is a small percentage of this European market. The UK today accounts for approximately 2% of the world market. By 2012 this will have reduced to 1%.

This study shows that it unlikely that special to purpose half duplex FDD devices will be produced for the European market. It is even more unlikely that country specific variants including products for the UK market will be supported.

We therefore conclude that the spectrum being released by Ofcom is unlikely to be supported by mass market terminals.

Acknowledgements
We have sought out a wide range of opinions for this study and the vendor community has been generous both in terms of original inputs and time spent on reviewing drafts. Thanks to all involved.

The market forecast and analysis was provided by our colleagues at The Mobile World.

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2) Background and context

Over the past 18 months, RTT have undertaken four study items for the GSMA, RF Cost Economics for Handsets published in May 2007, a UHF cellular handset study published in September 2007, a UHF LTE half duplex handset study and a short summary document on a 'Universal' UHF handset, both published in October 2007.

'RF Cost Economics' explores the present economies of scale in the industry and shows that markets that are dominant in terms of spectrum allocation, technology and/or geography and/or demography have a gravitational effect on R and D and engineering spending.[4] The study (92 pages) and a shorter White Paper can be downloaded from the RTT web site http://www.rttonline.com

By implication, handsets that have to be specially designed or adapted for smaller markets may be starved of engineering effort. There may be a smaller choice of handsets, handsets may be late to market and may be compromised both in terms of their cost, performance and end user functionality. This means that operators cannot realise a return on their spectral investment.

Country to country differences in the band plan may dictate that multiple RF front ends are needed. Country specific iterations imply additional design, engineering and optimisation effort and expense.

In parallel there have been ongoing discussions as to the operational bandwidth options, duplex spacing and positioning and size of the duplex gap.

Some of these issues were discussed in the UHF cellular handset study, the half duplex study and the 'universal handset' study.

The 'universal handset' was an attempt to show that it might be plausible to sub band the entire UHF band from 470 to 862 MHz such that one handset could be used on a world wide basis.

In practice, the differences between the US and European band plans are such that a 'universal handset' is unlikely to be realised at least within a foreseeable (five to seven year and probably longer) time scale.

Thus handsets for Europe have to make sense both technically in terms of the proposed European band plan and commercially in terms of European market volumes.

The option of half duplex was proposed as a mechanism for providing a measure of flexibility in terms of the duplex spacing and positioning of the duplex gap on a country to country basis and to allow when and where necessary for country to country band plans with a TX/RX overlap.

If it could be demonstrated that a half duplex handset is easier to design and manufacture than a full duplex handset and if it could be demonstrated that a common denominator half

[4] For example, according to our colleagues at **The Mobile World** as at March 2008 there were 557.8 million cellular subscribers in China with new subscribers being added at a rate of nine million per month. India has a similar growth profile. Servicing these markets is already an R and D priority for many component and transceiver vendors. Infineon for example issued a Q2 08 profit warning (28th May Financial Analyst announcement) due to delays with their single chip solution for Nokia ULC (ultra low cost) handsets. For companies like Infineon, addressing the specific needs of smaller regional markets, particular when those markets have non harmonized band plans would be financially foolhardy. Servicing individual country markets within these smaller regional markets would be even less attractive. These effects are quantified later in this study.

duplex design could service all European markets then this might mitigate possible scale economy issues.

Potentially half duplex may also yield a lower insertion loss due to a relaxed TX filter specification and a lower component count.

Implementing half duplex however implies additional standards work with associated time to market implications.

Nokia have suggested that the standards work needed could be included in 3GPP Release 8 or more comprehensively in Release 9. However the work would be given a lower priority than present full duplex and TDD work items.[5] This view has been corroborated from other industry sources.[6]

Release 8 at time of writing is scheduled for functional freezing end December 2008 and Release 9 end December 2009 with market availability following approximately two years later.[7]

This suggests that it is possible for half duplex handsets to be available by 2012 coinciding with the expected roll out of the first European 800 MHz LTE networks and or for LTE 800 networks in the UK.

However any slippage in full duplex or TDD standardisation will have a direct knock on effect on half duplex work items. This needs to be factored in to operator assumptions as to whether half duplex handsets could be standardised and then developed within the required

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[5] **Director Nokia Eutran activities Nokia Devices R and D 23/5/08**
In Nokia we do not see LTE HD-FDD to be such a big issue standardization work load wise (with the absolute requirement of maximal re-use of LTE-FDD and TDD standards and specifications). However - time wise priority has now to be on LTE-FDD and TDD. HD-FDD is a Rel 8 issue - in practice even a Rel 9 issue. Industry focus has to be now on FDD and TDD.

HD-FDD has some implementation merits and flexibility in deployment as you mention, but I do not see them as major issues - especially because **full FDD will need to be supported in terminals also because of e.g. roaming reasons.** If there is big interest for HD-FDD specifically on 800MHz then **the band plan should be such that full-FDD and HD-FDD both can be deployed**.

Additionally - **what ever the 800MHz band plan will be it should be a global allocation**. Country specific (like potentially in UK for 800) will suffer from economies of scale thus decreased competition **- with all known negative implications.**

[6] **Epcos**- response from CTO of the SAW components division 4th June 08 – Epcos take the view that the non availability of TDD systems and handsets shows that there is no appetite at component vendor level for any standards other than FDD at this time.

[7] **Senior member ETSI – comment on standards status.**
The target date for Release 8 functional freezing is December 2008. There is a lot of pressure for this date to be maintained. Usually, equipment appears on the market approximately two years after functional freezing. However, for LTE, there are a considerable number of trails already being undertaken (*cf* http://lstiforum.org/) which is unusual so far ahead of the game. We know that DoCoMo have publicly announced commercial launch of LTE by Q4 2009/Q1 2010 and so I would expect *some* products to be available by that time frame. Also note that Japan has made it clear that they will deploy a 3GPP compliant network *which implies that stable standards must be available by that time*.

There has been a lot of debate about the Release 9 scheduling. It is commonly expected that Release 8 will, by definition *contain many bugs*. Also, there will be a number of features which we already know will not be ready for December this year and so will slip into Release 9 (among which is likely to be IP voice support). It is therefore expected that Release 9 will be a short Release, issued soon after Release 8. My best guess is that it will be in December 2009.

time scales. Component vendors will not commit development resources until these standards issues are resolved.[8]

Note also the comments from the Nokia respondent in the footnote suggesting that it will anyway be necessary to support full FDD LTE 800 for some European markets. If this is the case then half duplex will not yield any cost benefit and implies an additional incremental design task. The RX and TX path will need to be characterised both for FDD and TDD operation.

Nokia also emphatically suggest the 800 MHz band should be a global allocation. This now seems to be a near impossible ambition.

There are a number of technical reasons why half duplex is interesting for LTE handsets. There are additional reasons why half duplex LTE may be technically interesting for the LTE 800 band (to overcome spectral harmonisation issues).

These benefits however can only be realised if sufficient engineering and financial resources can be made available.

Over the next five years, sales of handsets in Europe will decline, a consequence of market saturation. Over the same period, sales of handsets in China and India will more than double. Europe is already a small market in global terms and the gap will continue to widen. The UK is but a small part of the European market. This developing difference will dominate the allocation of engineering and investment resource. [9]

3) Arguments for and against half duplex

Let us consider the possibility (note this is not something that the industry wants!) of supporting separate band plans in an FDD LTE 800 European handset.

The band plans could be implemented using channel bandwidths of 5, 8, 10, 15 or 20 MHz.

Let us assume the band plans are structured around the allocations shown below in Figure 1 (chart reproduced from Page 8 of the ECC PT1 meeting 14/16 May 08 GSMA submission document with subsequent amendments).

The plans include an overlapping option (the top option) which is intended to provide a transceiver architecture that could potentially cover all other options.

If all options were half duplex FDD then it would not theoretically matter where the duplex gap was placed.

This opens up the prospect of a universal European LTE handset.

Figure 1 Possible Band Plans for LTE 800 in Europe

[8] **Comment from UK Operator 3/7/08**

An additional factor is the relative timing of decisions – if some European markets decide earlier than others (for example France, Sweden and the UK) there may be an effect where:

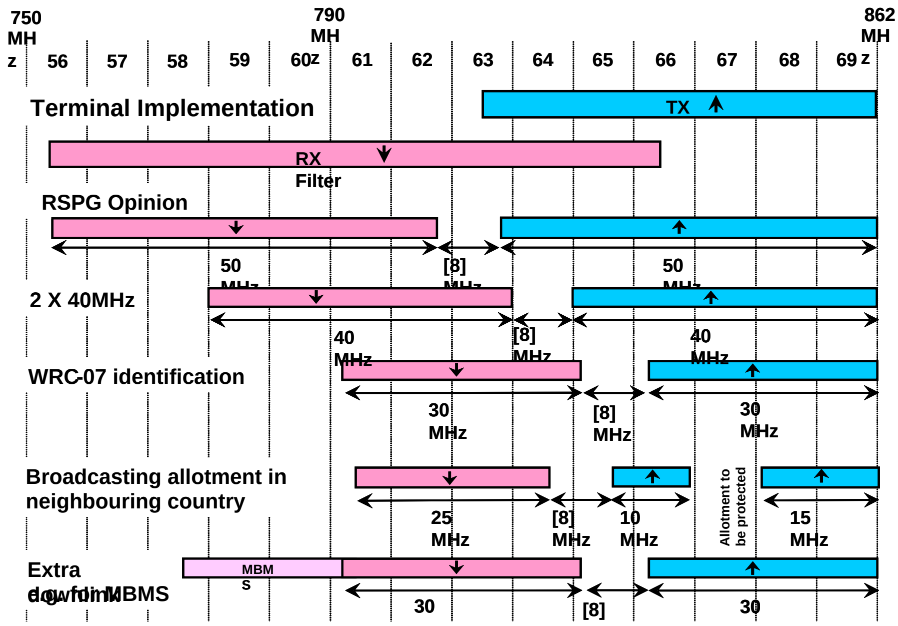
i) The first few movers are forced to wait (product availability is delayed beyond the 2/3 years implied above)

ii) Once (if?) sufficient opportunity/market emerges prior to any mandatory harmonisation decision that persuades vendors to develop components and equipment they will focus on the simplest (lowest cost to develop and/or certainty of return) solution;

iii) Markets that decide after that time will miss the boat if they choose a band / plan incompatible with the "adopted" solution. If so, how does this affect component/device cost and availability?

Alternatively, is there an argument that can be drawn that suggests a mandatory harmonisation measure is the only way to ensure that a viable solution emerges?

[9] Relative market sizes are quantified later in this study



Note that the band plans outlined above are done to consider terminal issues. Other factors might come into play when considering system deployments that impact on these band plans.

Identifying the bands starting with 'RSPG opinion' as A through E ,'A' (two by 50 MHz), 'B' (two by 40 MHz) and 'D' (25, 10 and 15) are 'unique' band plans and will each require their own duplexer.

'C' (30 by 30) and possibly 'D' (25, 10 and 15) might share a duplexer. It is possible to support a 6 MHz gap with an FBAR duplexer.

The cost of each duplexer in 2012 will be between 25 cents and one dollar depending on the severity of the band plan or the level to which a performance compromise is deemed tolerable. For example a two by 50 MHz band with an 8 MHz duplex gap would be over ambitious even for a carefully characterised FBAR filter so the issue for this option is predominantly compromised performance and or additional L and C components which would be inherently low Q devices.[10]

The dollar premium for full duplex could therefore be anything between $1.50 and let us say four dollars assuming (worst case) separate duplexers for each band and all bands included.

There will also be a real estate and insertion loss cost of the order of between 0.5 and 1.5 dB for the wider bandwidth filters.[11] This however depends on the multi throw switch performance including isolation and the linearity needed to prevent blocking.

Some vendors suggest a marginally higher figure.[12]

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[10] In 2002 CDMA BAW duplexers were available at a cost of $4 dollars. This had reduced to 2 dollars by 2004 but this cannot be taken as a linear trend. The cost of duplexers today is very much determined by the severity of the application and market volume. The 25 cent to one dollar cost boundaries for a 2012 handset have been confirmed as likely price points from two independent sources. For wider bandwidths there will be a requirement for additional external components unless a performance compromise is accepted.

[11] Estimates from Avago 16th June 2008

[12] According to Peregrine 22nd May 2008 eliminating the duplex filter and replacing it with a low pass filter on the TX path would save about 2 to 3 dB. The saving on the receive path will be less, of the order of 0.7 dB as filtering will still be needed. Comments from Peregrine 22nd May 2008

The half duplex handset will not have a duplexer and allows for all of the band plans shown in Figure 1 to be supported. There would be a reasonable prospect that the TX paths could be consolidated. On the RX path calculations suggest that an RX filter would be needed for each band.[13] Some of these might be able to be consolidated depending on blocking requirements.

If more rigorous protection is required from the RX filters then this could imply up to six receive throws. Note however the point made by Nokia and others that there will probably be duplexers in these handsets anyway to support full duplex band plans making any cost savings achievable with half duplex academic. Designing switch paths to support FDD (optimised for linearity) and half duplex FDD (optimised for low harmonics) will be problematic and probably result in path duplication.

Bandwidth calculations[14] show that the RX filter requirements are significant particularly for the 50 by 50 MHz band and the differential cost between half duplex and full duplex is therefore less than the $1.50 to $4 dollar boundary values implied above.

Quantifying this, if you can survive with four RX filters you will probably pay a premium of between $0.25 and $0.60 cents. If six are required then this increases to probably $0.30 to $0.75 cents. These are aggressive price points but consistent with present RX filter cost reduction trends.

However there is an additional operational bandwidth premium dictated by the need to have an increased dynamic range for the wider bandwidth handsets. This will have a DC power drain implication.[15] Additional DC power drain implies increased noise which implies decreased sensitivity.

It is also not correct to assume that the absence of a duplexer will automatically deliver two to three dB of sensitivity gain. Comparing RX filter loss to duplexer loss, the RX filters would be in the range of 1.5 to 2.5 dB while duplexers would be in the 2 to 3 dB range.

Additionally there are circumstances where physical proximity between two devices, particularly where one device is transmitting on a frequency which is being used as a receive frequency by another user will cause desensitisation. Additionally high level TV signals have to be filtered out of the receiver.

But let's say a half duplex handset could deliver a BOM saving of two to three dollars, some sensitivity gain probably of the order of 0.5dB under certain conditions, some improved efficiency on the TX path due to reduced filtering (an estimated 1.5 dB) and the additional flexibility of being able to support all of the required band plans.

This would appear to confirm some of the technical case for half duplex. However several caveats apply to this statement.

Let us say that the rationale for implementing half duplex is that it is the only way of supporting a band plan with a TX/RX overlap (no duplex gap) in order to accommodate all other band plan options. In the process all other variants (the other six variants identified in Figure 1) might be accommodated with the same filter configuration.

This however implies that the RX filter characteristics and other factors such as receiver dynamic range must be characterised for the worst case condition. Filters that have to work over extended bandwidths may have poor band edge performance or may 'sag' in the middle. Intuitively this implies that countries with relatively easy to achieve band plans would suffer unnecessarily poor or at best variable performance.

[13] This depends on a large number of assumptions, for example TV signal strengths, user to user spatial distribution, peak and average power levels and duty cycles.
[14] These calculations are included in the original study and are available on request.
[15] These effects were quantified in the previous half duplex study.

Alternatively multiple filter paths could be implemented for each of the other six band plans. This would mean that relatively optimum performance could be achieved for any given band plan. This is the case with GSM where dedicated RX filters are needed for each band.

On the TX path, the half duplex TX filter specification could be relaxed when compared to full FDD (no need to provide duplex protection). In practice the filter would become a low Q harmonic filter consisting of printed L's and C's rather than a band pass filter. The overall cost difference may be in the order of two to three dollars. However this may be more than off set by additional non recurring engineering costs and opportunity costs that would need to be recovered over relatively small market volumes.

Thus although the TX filter will have a relaxed specification, it will still need designing and characterising. This represents additional incremental design work if full duplex also has to be supported in the same handset.

In this case it is tempting to say that the phone may as well be full duplex,

So we come back to the assertion that half duplex is probably only worth pursuing if a 50 by 50 MHz band plan with overlapping TX and RX (so that other band plan options can be covered) is considered to be an overriding strategic objective for the industry. In this context, the relatively poor RF performance of a 50 by 50 MHz handset even when optimised adaptive matching techniques are employed should be an important consideration particularly if other handsets supporting less ambitious band plans suffer as a consequence.

This brings us to the other related issue of the need for harmonisation.

Essentially we are arguing that a one size fits all filter solution whether it is half duplex FDD or full duplex FDD may result in unacceptably poor performance for countries with relatively relaxed (narrower) operational bandwidths and an eight or ten MHz duplex gap.

There will therefore have to be multiple front ends for each of the bands. Note that adding six new DDR bands changes a ten band phone (four GSM bands, EGSM, PCS, DCS, five UMTS bands) into a 15 or 16 band phone without accommodating LTE 700. This may be beyond what switches can support on the basis of presently visible future technology options.

This is likely to be an unattractive R and D investment proposition for component vendors and or handset manufacturers (an unacceptable technical risk). In turn this implies a risk of limited handset availability and or time to market delay (an unacceptable commercial risk).

Half duplex does not mitigate this risk, rather it increases it. **Although in some ways half duplex can be presented as a simpler design task (relaxed TX filtering) this is not how it is presently perceived in the industry.**

The industry clearly and unambiguously considers half duplex as an unwelcome additional work item which will introduce incremental non recurring engineering costs and opportunity costs that will need to be recovered over relatively small market volumes.

Thus although half duplex may have merit technically and although half duplex may resolve some of the band planning issues for LTE 800 in Europe and the UK, there seems little practical prospect that the RF component industry, transceiver vendors and handset vendors will be willing or able to design and deliver half duplex handsets either within an acceptable time scale or at an acceptable cost.

If half duplex FDD could be shown to offer more generic benefits across all LTE bands then it might prove easier to justify but detailed work remains to be done to establish the potential merits/demerits of this option. The following section highlights some of these issues.

4) The past, present and future rationale for full duplex
When WCDMA was first specified for Release 99 the decision was taken to implement the air interface as full duplex FDD.

This represented a departure from GSM handset design which used (and still uses today) half duplex FDD in which TX and RX slots are separated within the handset by a time domain guard band.

From a handset design perspective, the decision to adopt full duplex FDD for WCDMA was determined by the requirement to preserve the AM components present in the modulated WCDMA signal. In particular there was a perceived need to avoid AM to PM effects which would translate any non linearity in the TX/RX signal path into phase error in the demodulated signal. Phase error effectively adds to the noise floor of the receiver and therefore directly degrades receive sensitivity.

Phase errors are introduced on the TX path by non linearity in the PA. Meeting TX EVM (error vector magnitude) requirements in early UMTS handset designs was problematic. It therefore made sense to avoid the higher peak powers used in GSM (up to two watts for a GSM900 handset or one watt for an 1800 MHz handset) and have the PA running at a lower maximum power (typically 250 milliwatts or less). The lower power helped deliver better TX efficiency and modulation accuracy.

Ten years have passed since these decisions were taken. Over this period there have been a number of advances in linearization techniques. These techniques when combined with improvements in RF component performance, including low noise oscillators, imply that TX and RX slots can be allowed to overlap in the frequency domain, at user to user level, without compromising the integrity of the modulated signal. Simply there is less wide band noise generated so user to user interference (which TDD does not protect against) is less of an issue and can generally be accommodated by the free space loss between adjacent users. Additionally the duty cycle in wider bandwidth HDDPA+/LTE channels will typically be low, of the order of one time slot per frame (1 in 15) for many applications.

In parallel the standards process has evolved (through Release 4, 5, 6, 7, 8 and 9) to embrace (In Release 8 onwards), OFDM modulation techniques that inherently provide better interference resilience. This robustness increases as channel spacing is increased, for example from 5 MHz to 10 MHz to 20 MHz.[16]

It might be assumed that the wider operational bandwidths, for example the 40 or 50 MHz bandwidth options would be more likely to support 10 or 20 MHz LTE channels. This is dependent on the number of operators sharing the band allocation.

Although greater interference resilience is achieved, these two factors (wider channel spacing combined with wider operational bandwidths) combine together to make the design task of implementing TX/RX filtering and TX linearity progressively harder.

Half duplex arguably relaxes the TX filter design task (assuming occasionally higher levels of user to user interference are accepted) but this is off set by the assumed requirement to support a higher maximum output power.

So there is a performance issue with the wider operational bandwidth options. **There is also a potential (though different) performance problem with the two by ten MHz option proposed for the UK particularly if multiple operators are expected to share the spectrum in a frequency domain multiplex. None of the wider channel spacing benefits of OFDM will be available. Additionally if half duplex was chosen it could result in lower per user uplink peak data rates. While this could be off set by increasing peak**

[16] Although overall channel resilience increases as channel bandwidth increases, the performance of a user specific channel will depend on the user data rate, coding, power and symbol cover and symbol distribution. This suggests there are a number of half duplex FDD system issues that require further study.

power output from the PA this would imply special to task characterisation of the PA including additional linearization.

LTE 800 handsets will be Release 8/Release 9 compliant and will use OFDM on the downlink. The uplink (mobile transmit) uses a new transmission scheme called SC FDMA. This is a hybrid transmission scheme that combines the low PAR characteristics of single carrier transmission systems used in GSM EDGE and WCDMA with the longer symbol timing and flexible frequency allocation (effectively the frequency domain spreading function) of OFDM.[17]

This is achieved by putting the TX signal path of the handset through a double FFT process.

LTE handsets therefore have similar[18] TX linearity requirements to UMTS handsets though with some additional baseband processing overhead (the double FFT).

The RX path in the handset however does have to process a conventional OFDM signal. On the one hand, this signal as we have stated is more resilient to interference. This translates into a lower C/N requirement at the demodulator. On the other hand, the signal is vulnerable to any frequency domain distortion which will translate directly into symbol error (a consequence of the FFT/inverse FFT transform).

We thus need to exercise caution when considering any relaxation of filtering on the RX path of an LTE handset. Note that future architectures commonly assume increased rejection in the RX filter to allow elimination of the RX filter **after** the LNA.

We also need to exercise caution when considering any relaxation of the TX path filtering in an LTE handset. Although half duplex provides time domain separation of the TX/RX path within the handset, it does not (as stated above) provide protection between two adjacent users. Note that pre PA TX filters are also assumed to be eliminated in future architectures. This implies more stringent demands on the filtering in the duplexer. Present targets have moved from typically 52 to 45 dB to typically 55 to 50 dB.

The motivation of introducing half duplex into the LTE800 band is primarily to help resolve European band planning issues. It allows different countries to deploy different duplex spacing, to move the position of the duplex gap, potentially reduce the duplex gap and in some cases eradicate the duplex gap altogether.

There may be a parallel opportunity to achieve a decrease in insertion loss particularly on the TX path which would translate into a reduction in DC power drain. At high output powers the RF PA still accounts for over 50% of the power drain in a cellular handset. On the other hand these savings are dependent on the typical power levels actually used by the handset, often in practice less than 5 dBm. These potential savings may therefore be overstated.

It is generally assumed that the LTE 800 band will be implemented as a reverse duplex with mobile transmit on the upper duplex and mobile receive on the lower duplex. This has the benefit of keeping mobile TX well away from any digital TV receive frequencies. It has the disadvantage that the RX path is exposed to relatively large TV signals.

The receiver dynamic range is determined by the dynamic range of the weakest link in the receive chain which can be any one of the components identified in Figure 2

Figure 2 Receiver Dynamic Range

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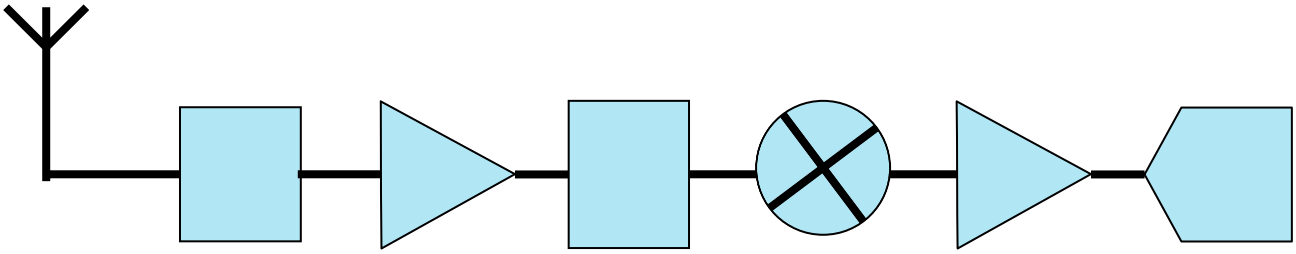
[17] Demystifying Single carrier FDMA- The new LTE Uplink Agilent White Paper, Moray Rumney, Lead Technologist, Agilent Technologies.

[18] Anecdotal experience suggests the specification for LTE is about 1 dB tougher than UMTS.



Dynamic range (the difference between the lowest and highest signals that the device can handle) can be increased but will result in a higher DC power drain. If a device draws more current it generally makes more noise.

On the TX path the benefits of the lower insertion loss with half duplex may be partially off set by the need to have a higher peak power (3 dB or more) to compensate for the 50 % reduction in duty cycle. [19]

A more persuasive reason to adopt half duplex may be the possibility that it would make it easier to implement the LTE PA into a single RF and baseband chip. (It stops the TX power coupling into the RX path). [20] Mainstream PA vendors remain sceptical that this will be achieved until well after the introduction of LTE 800 networks so this should not be taken as a major justification for half duplex implementation.

Essentially experience with GSM over recent years has set expectations that adding bands is easy and inexpensive. This is not the case for UMTS or LTE irrespective of whether the handset is full or half duplex.

The PA is no longer the dominant cost item or necessarily the most challenging design task. Designing and implementing multiple differential receive paths is likely to be a major headache irrespective of whether the device is half or full duplex.

A **single band** full duplex LTE800 handset with six possible TX/RX signal paths would be of similar complexity to an existing high tier multi band handset. Put another way, adding LTE800 to an existing handset doubles the TX/RX path complexity irrespective of whether the device is full **or** half duplex.

If the device is full **and** half duplex then the complexity increases again. So **any assumed benefits for half duplex have to be predicated on the assumption that there will be no parallel need to support full duplex operation for any market.**

There have also been discussions about adjacent channel leakage ratios (ACLR performance) and the impact of ACLR as channel bandwidths increase from 5 to 8/10 or 20 MHz.

In theory and practice, as channel bandwidth increases, spectral re growth, including the presence of higher order products increases. Spectrum re growth is a function of PA non linearity and is not filtered by the filter placed between the PA driver and the PA.

The third order spectrum growth dominates the out of band emission in the first adjacent channel, the fifth spectrum re growth dominates the out of band emission in the second

[19] There are counter arguments to this. Half duplex implies losing half the available time domain transmit bandwidth. However the more widely spaced LTE channels (10, 15, 20 MHz) will have a relatively low duty cycle and therefore the overall impact on peak data rates may not be significant.

[20] We cover this in more detail in Appendix 4

adjacent channel and the seventh order re growth dominates the out of band emission in the third adjacent channel.

Calculations[21] suggest that for channel widths of 8 MHz or above, the dominant source of noise desensitisation is a function of these spectral re growth components rather than PA noise power.

The unwanted signal energy is at a low level so does not affect the signal handling capability of the receiver but it does add to the noise floor.

The degree to which this occurs is a function of the linearity of the PA. The linearity of the PA is a function of the operational bandwidth over which the PA is expected to operate.[22] This is because the linearising techniques used work more effectively over relatively narrow bandwidths.

Therefore if the design aim is to produce a handset capable of supporting a 50 MHz TX bandwidth and/or using the same PA to cover LTE900 and/or LTE850 and/or LTE700 TX and/or to support wider bandwidth channels (8MHz and above) then it will be true to say that spectral re growth components will be an issue. PA linearity could of course be improved by backing off the PA but this will have an impact on TX efficiency.

Half duplex does not ease this performance constraint as it is a user to user noise transfer process.

It would also be harder to share a PA if the LTE800 half duplex PA and TX switch paths had to be characterised separately from an LTE 850 or LTE 900 (or LTE700) full duplex handset.

In general it has to be considered that most of the present design and optimisation work is being done on full duplex FDD handsets and their related component requirements and it can be expected that the performance of these devices will continue to improve over time.

Although half duplex offers some band flexibility benefits in terms of the positioning of the duplex gap it would appear that separate RX filter paths are still needed so the path complexity is similar for both options (though sufficiently different to be problematic). If both options have to be included in the handset this complexity is doubled.

5) Relative market volumes in 2012

This section has been researched by our colleagues at The Mobile World (TMW) using statistics from their world wide cellular subscriber data base.

The objective is to show the relative importance of five geographic markets by volume and value in 2012, Europe, North America, the Middle East and Africa, Latin America and Asia Pacific, including, separately, India and China.

From this, we aim to establish the RF component value of the cellular handset market in 2012 and to use this to qualify how much R and D spend (and conformance and production test spending) will be affordable and where it will likely be spent.

The methodology used is as follows:

Net subscriber additions are measured and recorded quarterly by analysing the financial results of all cellular operators. Churn rates are estimated where they are not available, to derive a number for gross new connections – the metric that is most relevant to determining the future size of the handset market.

[21] Qualcomm inputs to the ECC PT1 meeting 14th to 16th May 2008
[22] And the power and gain required from the amplifier

On a historic basis, (for the purpose of this analysis from Q1 2003), the ratio of gross subscriber additions to handset sales is analysed and then projected forward on a region by region basis.

Future subscriber growth forecasts by region are generated by a complex process which considers many demographic and economic factors. The first step is to determine the population and population growth rate (the net of births and deaths) for each particular market (using data mostly derived from the CIA Fact Book).

The population is divided into three demographics, under 15, 15 to 64 and 65 and over. In mature developed markets it is assumed 100% of the 15 to 64 age group will eventually own a mobile, 50% of the under 15 group and 75% of the over 65 group. This gives a base line for future mobile ownership, which increases, or decreases, according to the change in the size and shape of the population.

In addition to this, it is assumed that a significant proportion of the population will own a second mobile device as a result of their employment. The size of the workforce is estimated or taken from published data if available and deemed accurate. The number of unemployed (derived by the same method) is subtracted from this total. The percentage of the workforce that will eventually have a second mobile is then estimated.

Finally, TMW estimates what proportion of this total will own a third, data centric device.

This gives a notional "saturation point" for each market. These assumptions are then tested against historic data and recalibrated as necessary to produce forecasts of how rapidly any particular market will approach the saturation point which, in turn, generates customer growth forecasts.

These forecasts are weighted for observed distortions. For example, people in developing/emerging countries spend more than twice the percentage of GDP on cellular phones when compared to developed mature markets and typically, developing world markets enjoy faster GDP growth rates.

Figure 3 compares net subscriber additions by region

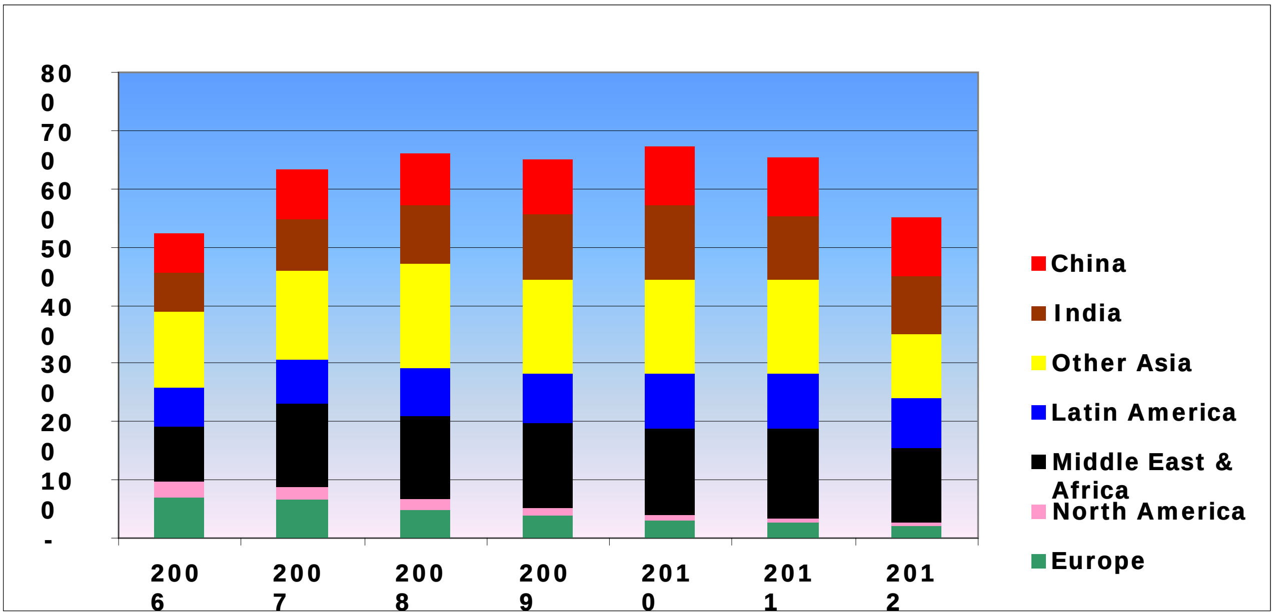
Figure 3 Table of Mobile Subscriber Growth (net additions) by region with percentage difference over 5 years, 2007 to 2012.

	2006	2007	% of total	2008	2009	2010	2011	2012	% of total
Europe	70	67	10%	50	39	31	26	21	4%
North America	27	22	4%	16	12	10	7	5	1%
Middle East & Africa	96	143	22%	145	147	147	156	129	24%
Latin America	67	75	12%	80	85	95	95	85	15%
Other Asia	129	153	24%	180	160	160	160	110	20%
India	67	87	14%	100	113	130	110	100	18%
China	68	86	14%	90	95	100	100	100	18%
Total		633	100%					550	

As can be seen, European net subscriber additions fall from 10% to 4% of the total over the five years from 2007 to 2012. (North America suffers an even more dramatic percentage drop suggesting that scale economy issues there may be more severe than Europe).

These relative shifts in subscriber additions by region are shown graphically below. Note that net subscriber additions are lower in 2009 and 2012. In the first instance, this is because of an anticipated slowdown in “Other Asia” as several key markets near 100% voice penetration. In the second, it is because the global market is nearing 100% penetration making incremental penetration harder to achieve.

Figure 4 Graph of annual net subscriber additions by region (m)



To determine the size of the handset market, we need to consider both the number of new customers connected in any one year and also the number of replacement handsets bought by existing customers.

Thus, our focus has to switch from using net additions to gross, in other words, the total number of additions before taking account of disconnections (churn).

Historically, the level of gross additions is fairly closely aligned to the number of new handset sales and we have used this as a guideline for our forecasts. The ratio of handset sales to gross additions (actuals to date and forecasts) are shown in Figure 6

Figure 5 Ratio of handset sales to gross additions in %

	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Europe	105	136	136	145	141	165	158	143	133	123
Middle East & Africa	68	32	33	48	46	48	50	53	55	58
China	63	70	74	79	85	95	96	97	98	99
Asia Pacific	100	89	77	63	60	59	60	62	63	65
North America	343	217	232	246	266	255	225	184	166	158
Latin America	70	85	84	82	74	68	70	72	74	76
Global	100	96	90	91	85	86	100	100	99	100

Applying the above ratios results in the following forecast handset sales by region.

Note that although net customer additions reduce slightly between 2007 and 2012, the increase in the ratio of handset sales to gross subscriber additions, particularly in developing markets, means that this market continues to grow, albeit at a decelerating rate.

Figure 6 Mobile handset unit sales by region

	2006	2007	%	2008	2009	2010	2011	2012	%
Europe	276	284	24%	298	266	237	215	191	12%
North America	160	170	14%	184	124	126	134	148	9%

Middle East & Africa	106	126	11%	156	180	214	256	280	17%
Latin America	118	130	11%	142	170	209	248	279	17%
Other Asia	176	241	20%	215	235	258	290	290	18%
India	55	71	6%	92	105	133	135	140	9%
China	129	173	14%	214	231	249	263	276	17%
Total	1020	1195	100%	1,301	1,311	1,425	1,540	1,604	100%
Year on year growth		175		106	10	114	125	64	

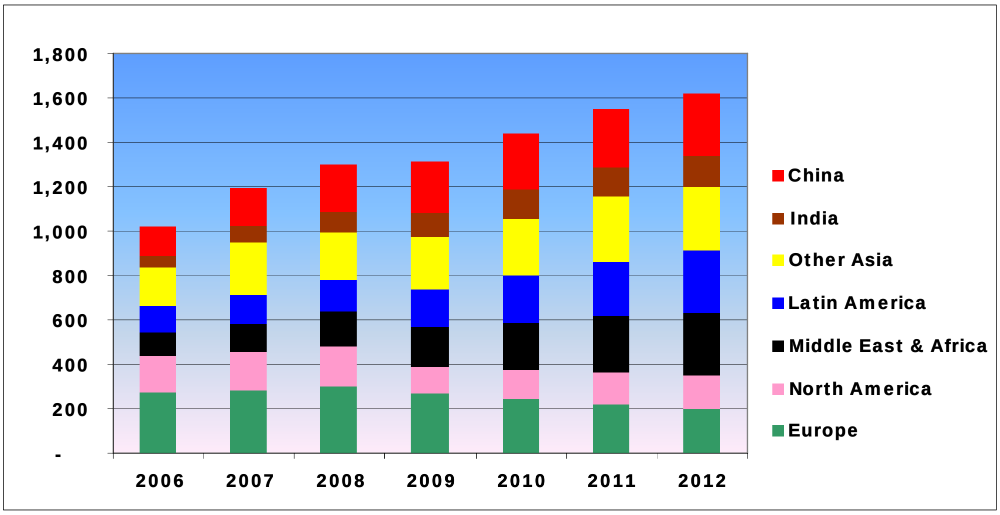
European market volumes are expected to decline from 284 million units to 191 million units over the five year period from 2007 to 2012 and reduced from 24% of the global market to 12%. Similarly, North America is expected to drop from 14% to 9%.

In Europe, these reductions are compounded by a decline in the ratio of handset sales to subscriber gross gains, (141% in 2007 down to 123% in 2012). This reflects a growing unwillingness to subsidise devices on the part of the operators. As a result, whereas the European market is expected to be 40% larger than the Chinese in 2008 (by volume) the positions reverse over the five year period to the point where China is nearly 50% larger than Europe. By 2012, the combined Chinese and Indian markets are expected to be more than twice the size of the European market and larger than the combined US and European markets (416m against 339m) thanks, in part, to an increasing demand for more frequent replacements at the top end of the market.[23]

This differential will continue to widen as the ratio of handset sales to subscriber gross gains increases in emerging markets.

The effect is shown graphically in Figure 7. Note how the growth over the period is almost exclusively derived from developing world markets (China, India and Africa) while sales in Europe and the USA peak (in 2008) and then decline for the remainder of the forecast period.

Figure 7 Mobile handsets- unit sales by region, 2006 to 2012



This is however not the whole story. As presently defined, Europe does not represent a single market for a Universal LTE800 handset but several markets, each of which either has to be

[23] Replacement cycles in Europe could lengthen as a consequence of an economic slowdown and general price inflation. This could further increase the market 'distance' between Europe and Asia and would certainly have an impact on available funding for RF engineering investment.

separately addressed technically (multiple path front ends) or addressed with a half duplex architecture which remains as yet undefined.

To reaffirm the general opinion expressed in other parts of this study, it will be a challenge to get the RF component community to focus on developing bespoke front end solutions for a minority market (LTE800 in Europe) which in addition is spectrally fragmented. This applies both to full duplex and half duplex handsets.

None of the respondents to this study perceive half duplex as in any way making the LTE800 design task easier or more attractive either financially or commercially.

The only possible argument that emerges from the above statistics is that China's present promotion of TD SCDMA might pull through additional TDD development and standardisation effort that could be repurposed into half duplex FDD/TDD work items.

However this would imply a closer coupling of Chinese standardisation effort with European standards work. This might be considered to have competitive implications for European and US vendors and their operator customers. Nokia's strong presence in the China market (see footnote below) gives them potentially substantial exposure to the local TDD market there if it develops but this is no guarantee that TDD and/or half duplex FDD would be encouraged to gain traction in other markets.

Figure 8 UK as a percentage of the world market

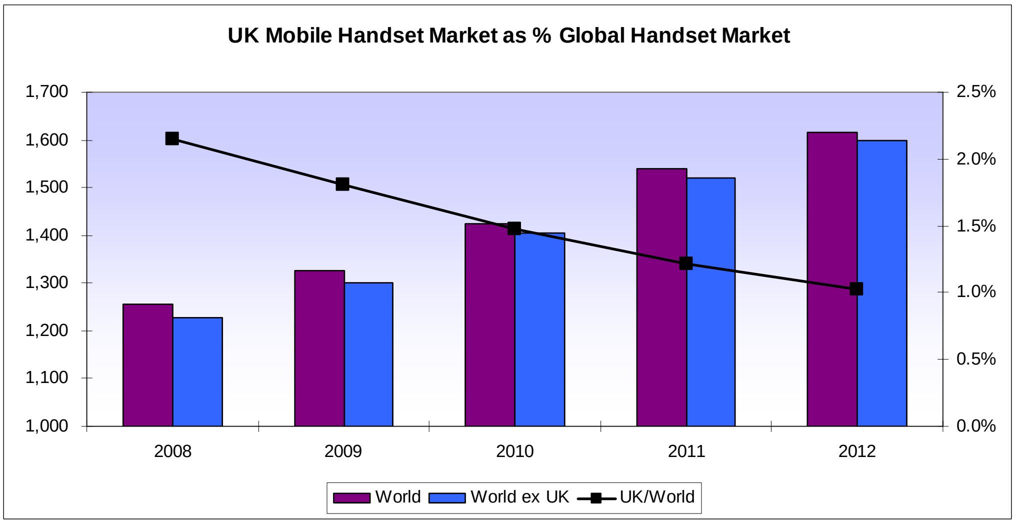


Figure 8 shows the impact that this market shift has on the relative importance of the UK in terms of global volume. Today the UK accounts for 2% of the world market. By 2012 this will have reduced to 1%.

6) Recovery of non recurring engineering costs
In the original RTT study we identified that the opportunity cost associated with servicing a non standard band was of the order of $300 million dollars.[24]

As implied above, UK unit volume in 2012 would be of the order of 16 million handsets per year (one per cent of total world unit sales of 1.6 billion).

This would imply an additional cost on a handset of 18.75 dollars assuming an NRE amortisation period of twelve months. This assumes that opportunity costs remain stable over the next five years whereas in practice they are more likely to increase as the overall market size increases.

[24] RF Cost Economics for Handsets White Paper Page 16 downloadable from www.rttonline.com

Additionally this calculation does not account for the possible cost of time to market delays or limited device availability dwarfed by any time to market delays.

As a specific example, the AWS band in the US (at 1.7/2 and 2.1 GHz) presently has a significantly narrower choice of handsets then other US bands. New HSPA+ devices presently sampling to the handset vendor community specifically exclude support for AWS.[25]

7) Markets by value - implications for radio frequency engineering investment
Of course market unit volume is only half the picture. We also need to have some idea of what the market value might be in 2012 and specifically the RF BOM revenues and margins. Working backwards we can then see how much 'real' money is available for R and D (including conformance and test investment). In practice this underlines the assertion above that opportunity costs may increase rather than decrease over time.

The following are 'The Mobile World' calculated blended average selling prices for Nokia handsets (GSM and 3G) in Q1 2008[26] designated in Euros with approximate dollar equivalents in our five markets of interest.

Figure 9 Nokia Average selling prices Q1 2008

Europe	North America	Middle East/Africa	Other Asia	China
126 Euros	95 Euros	74 Euros	71.5 Euros	70 Euros
£105	£79	£61	£59	£58
$202 dollars	$152 dollars	$117 dollars	$113 dollars	$112 dollars

There are several points to make here.

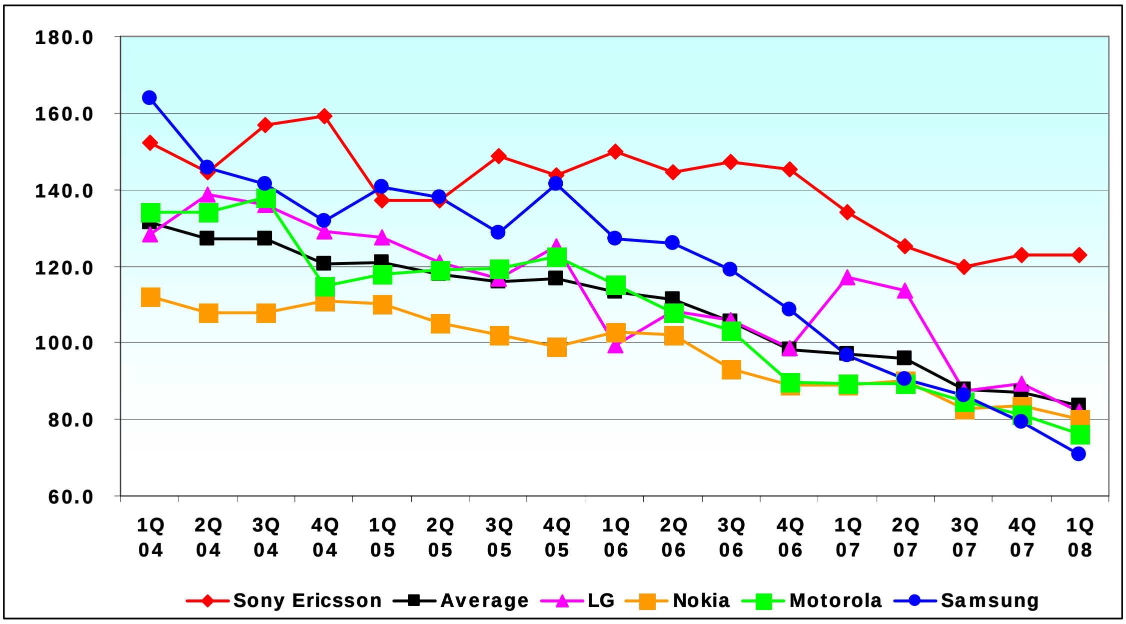
First the ASP's In Europe are double the ASP's in China.

This does not mean that the margins are double but rather that the mix of products is different in these two markets.

Secondly these prices have historically declined by 12% per year. In Q12004 the average selling price globally was 131 Euros declining to 80 Euros by Q12008 quarter by quarter. (Metrics derived by The Mobile World from published financials).

Figure 10 Mobile Handset Average Selling Prices Q1 2004- Q1 2008 (€)

[25] As an example, at a recent analyst briefing ((August 1st 08) Qualcomm stated that their GOBI HSPA+ chip set would not support the AWS band.
[26] Derived from Nokia financials.



Thus the global average by 2012 on a linear progression basis would be 47.92 Euros (76 dollars) though the increasing importance of China and India may result in a more aggressive decline.[27]

However for Nokia at least, average handset costs have declined at a faster rate of about 15% per year over the past two years. As a result, Nokia's profit margins have been increasing and are now above 20%, far above the industry average. It is interesting that throughout the period shown in the graph above, Nokia's ASP has been consistently below the industry average. In part, this is a function of the mix of shipments, but research by The Mobile World suggests that this is a deliberate policy and that Nokia will therefore continue to reduce prices, to maximise its market share and put ever-greater pressure on the profitability of its competitors. [28]

Therefore an average blended global BOM in the region of 30 dollars in 2012 is plausible. This would suggest that the 'budget' for RF components could be close to two dollars.[29]

This still represents over three billion dollars of annual turnover (assuming handset unit volumes of 1.6 billion). The question is whether this is profitable turnover that can deliver a reasonable return on R and D and foundry investment for the RF component community.

The RF BOM of course will be higher in mid or higher tier phones but these handsets may also be supporting Bluetooth, WiFi and NFC radio functionality, a GPS receiver and DVB H receiver.

This brings us to the issue of how many RF vendors will be competing for this BOM share.

[27] The counter argument here is that the need for multi band and multi mode in many markets will force the RF BOM cost in the opposite (upward) direction. In this context it is hard to see how a year on year real cost decrease of 15% can be sustainable.

[28] Each of the big 5 handset manufacturers have very different geographic market share. For example Nokia shipped 116 million units in Q1 2008 of which 26 million were into Europe. Their single largest market was Asia Pacific with 55 million units. 20 million units of the 55 million went into China.

[29] The RF cost component as a % of the overall BOM of the handset has remained remarkably consistent over time. These cost metrics are analyzed in detail in the RF Cost Economics study.

Most of the cellular industry supply chain has become aggressively consolidated and it is hard to see how this will change by 2012. Arguably the consolidation process will continue in order to reach the cost targets needed to maintain year on year unit volume growth and to fund the required engineering investment.

By aggressive consolidation we mean no more than five tier 1 players at every stage of the industry value chain, with the five players between them servicing at least 70% of the total market by volume and value.

So for example this would suggest five operators world wide, each with a different geographic mix but with a global presence, five infrastructure vendors with a similar market hold, five handset manufacturers and five based band silicon vendors, for example today, TI, Qualcomm, ST Micro/NXP, Media Tek and Infineon.

If this was the case in the RF components sector then a market value of three billion dollars would suggest simplistically a $600 million dollar annual market per vendor as an average addressable market.

However the RF components sector does not obey the five player rule.

Within the cellular BOM there are antenna vendors (Pulse, Antenova, Ethertronics, Sarantel, Fractus), RF shielding and antenna vendors (Lairdtech and WL Gore), RF PA vendors (RFMD, Skyworks, Avago, Triquint, Anadigics)), PA technology start ups such as Nujira and Axiom, filter vendors (Murata, Epcos, Avago, Fujitsu and Panasonic, switch vendors and RF MEMS specialists (Peregrine, Wispry, Paratek, SiTime , Discera) and vendors whose stated aim is to integrate all of the above (Triquint, Skyworks, Avago).

Additionally, Bluetooth vendors such as CSR are competing for Bluetooth and Wi FI value, companies such as Atheros (with a strong legacy in WiFi) and DVB H vendors such as Mirics all have competing claims for an RF BOM which if present trends are indicative reduces in value every year.[30]

The inevitable conclusion is that the RF component sector of the industry is overdue for consolidation if the addressable market by volume and value is taken into account.

Similarly test equipment vendors (five major vendors but two with specific RF experience) will have to develop customised test routines for half duplex.

Taken together these factors suggest that there will be very little surplus R and D spending and conformance and production test budget available for markets with unproven volume and value. Although Europe, as the figures state has a significantly higher ASP than other world markets, this is a reflection of handset product mix. In other words these markets absorb a higher percentage of mid tier and high tier handsets. Although the RF BOM in these handsets is higher, there are more vendors competing for the value, including as stated GPS and DVB H, Bluetooth, WiFi and NFC vendors. [31]

Additionally consolidation may slow rather than hasten device innovation. In the RF Cost economics Study we referenced for example an initiative between Lairdtech and RF Micro

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[30] For example the cost of adding GPS is presently $5 to $10 dollars http://www.csr.com/pr/pr268.htm with many of the silicon vendors (CSR, SirF, Broadcom) making aggressive claims of reducing this to a sub two dollar price point, still very significant even in a mid or high tier handset. At this point much of this peripheral radio functionality will be integrated into the CMOS baseband RFIC control chip.

[31] The higher realized prices in Europe are partly a function of this additional RF functionality. This implies significant additional standards work and RF integration effort. Adding half duplex FDD to this work load would be problematic. Conversation with CSR 26th June 2008.

Devices to deliver innovative integrated shielding and transceiver solutions to the market.[32] This initiative has not progressed.

Apart from underlying the obvious (Press Statements as an expression of ambition rather than market reality) this shows that attempts at consolidation and cooperation in the RF component sector are prone to failure.

The counter argument is that these separate RF areas demand focus and specialisation.

Even taking this into account, a general willingness or ability to support half duplex design projects for the European LTE 800 band must be regarded as highly questionable. Similar constraints might be assumed to apply to the US LTE700 band in terms of market scale economy. A willingness to support handsets that have to be separately optimised for the UK is inconceivable.

8) Are there other device innovations that should be considered?
This of course would not be the case if some form of software defined radio could be developed that offered band plan flexibility at an acceptable price and delivering acceptable performance.

However the mass market software defined radio remains an elusive ambition. This can be simply explained by studying the component requirements in a software defined radio, including specifically the requirement for flexibly tuned resonant components. RF MEMS are one of the key enabling technologies.

We last looked at RF MEMS in the RF Cost Economics study. This study was published in May 2007 but was based on research from the prior October. Therefore nearly two years have elapsed. This provides us with a reason to revisit progress on the 'software defined radio.'

As a reminder, **R**adio **F**requency **M**icro **E**lectro **M**echanical **S**ystems are very small (nanoscale) devices. They are already widely used in cellular phones as duplex (FBAR) filters. Their application is potentially being expanded to include MEMS switches, inductors (providing the basis for tuneable filters), resonators and tuneable capacitors.

RF MEMS are not a technical panacea and as with all physical devices have performance boundaries. For example if a device is designed to tune over a large frequency range it will generally deliver a lower Q than a device optimised for a narrow frequency band.

An alternative approach is to exploit the inherent smallness of RF MEMS devices to package together multiple components. For example Wispry's first sample tuneable digital capacitor is an array of 80 digital capacitors on one die. [33]The purpose of these devices is to produce adaptive matching to changing capacitance conditions rather than to tune over extended frequency ranges within a band.[34]

The commercial merits and demerits of RF MEMS have been discussed in earlier studies[35] - essentially over exaggerated performance and reliability claims over the past few years have resulted in a measure of caution in terms of mass market adoption.

[32] News release St Louis June 27th 2007 Business Wire – Laird technologies, the worlds leading handset manufacturer with over one billion handset antenna shipments announced an agreement with RF MD to jointly develop RF systems for the wireless industry.
[33] Wispry claim this device will be used in a handset being introduced in 2009.
[34] Wispry point out (e mail 30th June) that these devices do work across all 3GPP bands and help optimize performance. Compensation for antenna effects and circuit variation is an added benefit.
[35] For example in the RF Cost economics study.

This in turn has made it difficult for vendors to generate sufficient cash flow to cover R and D expenses.

Teravicta, one of the early innovators in RF MEMS switches filed for Chapter 7 bankruptcy in February 2008 and it is generally fair to say that return on investment for the RF MEMS pioneers has been to date disappointing.

However this may be changing.

i) FBAR filters as an example of the technical and commercial maturation of RF MEMS
Avago claim to have shipped over 750 million FBAR filters for use in cellular handsets.[36] The devices are encapsulated using wafer to wafer bonding, a technique which Avago are presently extending to a new range of miniaturised RF amplifiers to be packaged within a hermetically sealed 0402 package.

FBAR filters demonstrate that RF MEMS can deliver useful performance improvements in cellular phones (higher Q filters with adequate temperature stability and lower insertion loss), meet aggressive cost expectations and meet quality and reliability requirements.

In parallel the industry has matured commercially. In April this year Epcos, the former Siemens Matsushita SAW filter business, acquired the RF MEMS assets of NXP Semiconductors for ten million Euros (approx 14 million dollars).[37] The stated objective is to change their business from essentially a one product company (SAW filters) to become an integrated vendor of adaptive front end modules.

RF Micro Devices have stated similar ambitions.[38] Avago with a strong presence in power amplifiers, filters, duplexers, switches, diplexers and integrated front ends could also be an agent of industry consolidation.

ii) Tuneable capacitors and adaptive TX and RX matching techniques
In common with a number of other vendors (RF Micro Devices, Wispry, Peregrine, Paratek see below), Epcos are targeting tuneable capacitance applications in cellular phones, initially for adaptive matching.

The company has stated that devices will be commercially available (in mass production) before the end of 2009.[39]

The rationale for adaptive matching is that it can deliver TX efficiency improvements by cancelling out the mismatch caused by physical changes in the way the phone is being used.

A hand around a phone will change the antenna matching, particularly with internal antennas. A gloved hand will have a different but similar effect.

Mismatches also happen as phones move from band to band and from one end to the other end of a band. TX matching is done by measuring the TX signal at the antenna.

In practice the antenna impedance match (VSWR) can be anything between 3.1 and 5.1. This reduces to between 1.1 and 1.5 to 1 when optimally matched.[40]

Adaptive matching of the TX path is claimed to realise a 25% reduction in DC power drain[41] in conditions where a severe mismatch has occurred and can be corrected.

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[36] Avago Press release 12th May 2008 Avago Wafer cap, industry's first semiconductor based chip scale packaging announcement.
[37] April 2008 Epcos Press Release
[38] RDMD Press Release 21st February 08 Flexible RF front end for Bands 1,II, III,IV,V,VI,VIII and IX
[39] Epcos investor briefing May 6th 2008
[40] Peregrine 22nd May 2008
[41] Epcos press release as above

However in a duplex spaced band matching the antenna on the TX path to 50 ohms would produce a significant mismatch of the order of several dB's in the receive path.[42]

Ideally therefore the RX path needs to be separately matched (noise matched rather than power matched). This is dependent on having a low noise oscillator in the handset such that it can be assumed that any noise measured is from the front end of the phone rather than the oscillator. Matching can then be adjusted dynamically.[43]

One vendor claims that this is easier in half duplex as the TX and RX optimisation can be carried out sequentially. Tuneable digital capacitors can be retuned in approximately 10 microseconds suggesting that there is enough time available between TX and RX slots to do this.[44]

Other vendors are less confident that the whole adaptive process (including accurate measurement) could be achieved within the TX/RX slot time and better results would be achieved with separate adaptive functions. [45]

Peregrine and Wispry both have substantial information on their tuneable capacitor products on their web sites. Note that these adaptive techniques rely on analog bias control and DC to DC conversion. These techniques in themselves consume energy and create noise and thus represent a non trivial design and implementation task.

RF Micro Devices promote the active (adaptive) TX matching on their RF 6285 multi band power amplifier module. The device is intended to be capable of supporting Band 1(present UMTS 1900/2100 MHz), Band II US PCS at 1900 MHz, Band III (GSM/UMTS 1800), Band IV (the AWS 1700/2100 band in the US), Band VI (the 800 MHz band in Japan), Band VIII (the GSM/UMTS900 band) and Band IX (the 1700 MHz band in Japan).

Adaptive matching is by present indications one of the more promising new techniques for use in cellular phones. The technique is essentially agnostic to the duplexing method used. It does however offer the promise of being able to support wider operational bandwidths though this in turn depends on the tuning range of the matching circuitry, the loss involved in achieving the tuning range and the bandwidth over which the tuning works effectively.

iii) Performance issues for other UMTS/LTE bands

In general there is a need to deliver sensitivity and selectivity improvements for bands with relatively narrow TX/RX spacing including existing GSM bands where UMTS/LTE will be supported.

Figure 11 taken from 3GPP TR25.816 V7.0.0 (2005-12) shows the difference in specified conformance sensitivity across seven of the 3GPP band plans proposed for UMTS/LTE deployment. The bands with a duplex gap (Min Tx/Rx spacing) of 35 MHz or more are specified to have a UE RX sensitivity of -117 dBm, Band V (the US 850 band) is specified at -115 dBm (a duplex gap of 20 MHz), and Band VIII (UMTS900) is specified at -114 dBm (a duplex gap of 10 MHz). Extending the duplex gap beyond 35 MHz makes little difference. The figures assume a 5 MHz channel raster and are based at present on expected UMTS transceiver performance.

Figure 11 (Table 31A from TR 25.816)

[42] Information from Peregrine 22nd May 2008
[43] A low noise oscillator is however expensive and current hungry.
[44] Peregrine 22nd May 2008
[45] Response from Wispry 27th May 2008 'If there is a single dynamic matching circuit, it is very unlikely to be able to switch quickly enough for 1/2 duplex. If a single matching network covers both TX and RX on the transceiver side of the duplexing or if separate networks are used for TX and RX on the transceiver side of the duplexing then the matching network will work equally well for both half and full duplex.

Table 31A

Operating Band	UL Frequencies UE Tx Node Rx (MHz)	DL Frequencies UE Rx, Node Tx (MHz)	UE Rx sensitivity (dBm)	Rx bandwidth (MHz)	Min Tx/Rx Spacing (MHz)
I	1920 – 1980	2110 – 2170	-117	60	130
II	1850 – 1910	1930 – 1990	-115	60	20
III	1710 - 1785	1805 - 1880	-114	75	20
IV	1710 - 1755	2110 - 2155	-117	45	355
VI	830 - 840	875 - 885	-117	10	35
V	824 - 849	869 - 894	-115	25	20
VIII	880-915	925-960	-114	35	10

A wider duplex gap implies a wider duplex spacing which together translates into increased sensitivity in a full duplex FDD handset. The impact of implementing half duplex FDD in to handsets operating in these bands is open to discussion. The bands with a narrow duplex gap will be more susceptible to user to user interference to which half duplex FDD affords no protection. Half duplex handsets operating in bands with a narrow duplex spacing could perhaps benefit from a relaxation in TX filtering but only if half duplex was universally deployed which seems unlikely.

Perhaps the point to be made here is more commercial than technical.

RF MEMS based technologies offer solutions for a number of design challenges introduced by the proliferation of existing bands and the introduction of UMTS and later LTE in to existing GSM bands (UMTS/LTE 850, UMTS/LTE900, UMTS/LTE 1800, UMTS/LTE1900 plus more).

These design challenges could be regarded as priority work items and are likely to attract development effort and R and D investment. LTE in the 2600 MHz band will demand a similar level of prioritisation. Other bands such as the LTE 700 band in the US have attracted substantial (close to $20 billion dollar) investments and will likewise demand (though may not receive) engineering attention.

This helps to explain the lukewarm enthusiasm that many component vendors and transceiver developers have for the European LTE 800 band in general and the LTE 800 half duplex option in particular.

Half duplex does not make the prospect of developing LTE 800 handsets for Europe any more attractive rather it makes it less attractive. A UK specific variant would be even less attractive.

iv) Power amplifier issues and possible relevance to the LTE 800 MHz half duplex debate

There may of course be some potential commonality between UMTS/LTE900 and UMTS/LTE800.

For example product statements from RF Micro Devices[46] clearly signify their intention to deliver tuneable power amplifiers as the next step towards software defined radio products.

Combined with active matching it is plausible that a greater degree of PA re use may be possible. For LTE 800 to use the same power amplifier as LTE900 would imply covering an operational bandwidth of over 100 MHz (810 to 915 MHz) at a centre frequency of 862 MHz.

[46] RF MD Product announcement 5th December 2007

This is 11.6% of the centre frequency, [47] For example the 1800 MHz band is 4.3%. It would likely be unacceptable to accept any efficiency loss for a UMTS/LTE 900 handset incurred as a consequence of needing to also support LTE 800. This implies incremental R and D spending in order to deliver an acceptable technical solution. The general consensus is that 15% is OK, 30% is stretching things too far which would mean a power amplifier covering say 698 to 915 MHz would be unlikely to meet efficiency and or EVM and or spectral mask requirements.

At present RF Micro Devices public statements would suggest that they will aggressively address these areas with announced plans to build a dedicated 200mm wafer fabrication plant for tuneable power amplifier modules with integrated TX/RX switches and mode switching.[48]

However these ambitions have to be considered in the context of more recent announcements of reduced investment by RFMD in cellular transceiver R and D.[49]

Just because something can be done and should be done does not mean it will be done.

As with other RF devices it is hard to see why half duplex would make frequency specific R and D investment in LTE 800 power amplifiers any more attractive.

The PA will be characterised differently from full duplex with a higher max output power (at least 3 dB to compensate for the 50% reduction in duty cycle and possibly higher). Consolidated power amplifiers will be optimised for FDD (linearity) not TDD (harmonics). Stretching the bandwidth for full duplex is probably easier than half duplex.

The power in full duplex has to be delivered through a highly specified (linear) RX/TX switch. The half duplex switch needs low harmonics. The design issues of the PA and switch paths are well understood but if both full and half duplex paths need to be supported then the design and implementation becomes problematic particularly when all the other existing switch paths are taken into consideration.

Thus half duplex represents an additional incremental design task with associated non recurring engineering expense which needs to be recovered from a relatively small market in global terms.

There may of course be arguments for implementing LTE900 as half duplex (in addition to other bands, see above) but this topic is outside the scope of this present study.

To quote the response from a Tier 1 PA vendor

'Economies of scale have and will continue to drive the market.

Lead players in LTE will attempt to harmonize requirements over all operators in order to limit the degree of fragmentation in their supply chain.

Full duplex is the common denominator so its very likely that at least the PA modules will be required to support full duplex, even in terminals down graded to half duplex'[50]

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[47] PA operational bandwidths of up to 20% of centre frequency are now possible though with some performance compromise. This is an area where substantial recent progress has been made (conversation with Avago 13 June 2008) for example Skyworks and RFMD have multiband power amplifiers that cover 1710 to 1980 MHz, a bandwidth of 13%.

[48] RF Micro Devices Introduces MEMS technology for functional integration of RF 5th December 2007 Product news

[49] Business News 7th May 2008 RFMD currently expects to eliminate product development expenses relating to its wireless systems business by approximately $75 million this fiscal year beginning in the June 2008 quarter.

[50] Response from Renesas 28th May 2008

There are start up technology companies such as Nujira who are promoting the possibility of wide band amplifiers where one PA (with suitable linearization and adaptive matching) can replace two or three existing power amplifiers. The approach promises overall reductions in DC power drain and heat dissipation and cost and board real estate.

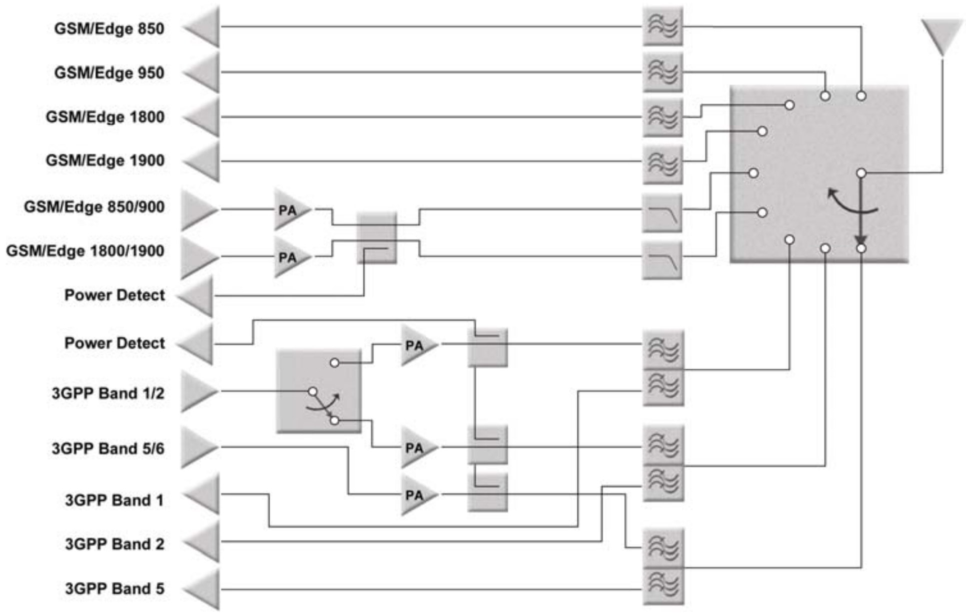
Such techniques and their successful implementation, whenever that may be, will generally be welcomed by the handset vendor community. However, as stated above, half duplex implies power amplifiers whose behaviour and performance will be sufficiently different from full duplex to imply an additional design challenge.

v) Path Switching for LTE 800 half duplex or full duplex
Figure 11 above describes the band plans that will need to be supported in an LTE handset even without taking LTE 800 into account.

Figure 12 shows a single pole nine throw switch made by Peregrine

This at least shows that very complex multiple switch paths can be supported in a handset.

Figure 12 Peregrine Single Pole Nine Throw Switch



Peregrine make the following point about half duplex versus full duplex

'Full-duplex signals are typically much more sensitive to inter modulation distortion in the antenna switch, so half-duplex is much easier in that respect. However, our multi-mode antenna switches are already fully WCDMA IMD compliant, so for us it makes little difference whether LTE signals are full or half-duplex.

From an antenna switch standpoint the switch core isn't that different between a full-duplex LTE versus separate RX and TX branches. Obviously the throw count of the antenna switch will increase when going from full-duplex to half-duplex, unless existing GSM RX filters can be re-used for LTE RX for example (depends on the band combinations).[51]

In summary, RF MEMS technologies do not have a major influence on the half duplex versus full duplex debate. The present consensus within the RF MEMS industry is that active adaptive matching will become more pervasive in near future handset designs and that this will likely be a well accepted performance optimization technique by the time LTE 800 handsets are needed (2012).

[51] Response from Peregrine 22nd May 2008

This may make wider operational bandwidths more achievable, for example the 50 by 50 MHz proposed channel band plan though filter performance will remain challenging for the foreseeable (five to seven year) future.

Note that wider operational bandwidths by default increase the noise and interference both visible to the handset and created by the handset. For example on the RX path, devices will need to have a higher dynamic range. These will increase their DC power drain. A higher DC power drain implies a higher noise floor. A higher noise floor implies reduced sensitivity.

Paratek are suggesting that more significant flexibility options will be available within these time scales. Paratek have a proprietary process based on thin film ceramic materials whose dielectric constant varies with the application of a DC voltage – the associated products are called Parascan. tm

The devices, including band pass filter modules are used presently in military and public safety software defined radios.

Due to competitive sensitivity it is hard for us to judge how advanced discussions might be to commercialize these techniques in cellular handset transceivers.

Plausibly such techniques would relax the need for spectral harmonization and the half duplex versus full duplex debate would become irrelevant. The consensus view is that this presently remains an ambition rather than a practical reality.

One reason for caution is that all parts of the TX/RX path have to evolve in parallel. For example one RF MEMS vendor commented that they had reached an advanced stage of development with a digital duplexer for a handset manufacturer but the project was moth balled due to lack of progress with tunable and/or broadband linear power amplifier modules.[52]

The availability of a digital duplexer would of course make half duplex unnecessary for all options except the overlapping TX/RX option.

vi) Is there enough profit in the RF BOM to sustain this sort of development?
This returns us to our running narrative that just because something can be done and should be done does not mean it will be done. Put another way, commercial constraints and opportunity costs may often delay the practical availability of potentially useful innovations.

The financial health of front end module vendors is therefore an important factor in assessing component time to market availability.

RF device innovation and the commercialisation of new RF devices remains expensive. Significantly non recurring development costs and commercialisation costs are increasing rather than decreasing over time.

The recent Epcos acquisition of NXP's RF MEMS activity provides an example. The acquisition in April 2008 cost ten million Euros (Fourteen million dollars). Epcos have stated that they are presently investing 6% of their SAW component revenue in R and D. These revenues are presently running at about 360 million euros suggesting an annual R and D expenditure of just over 20 million euros. The first mass produced RF MEMS tuneable matching networks are expected in 18 months.[53] Note this is tuneable matching not a tuneable front end which remains a more distant prospect.

We have already referenced RF Micro Devices stated intention to invest in a specialist RF MEMS fabrication facility. Such investments are a hazardous undertaking as **Filtronic** and others have previously demonstrated and require large established and stable market volume and value to be profitable.

[52] Conversation with Wispry 20th May 2008
[53] Epcos investor briefing May 6th 2008 as reported generally in the financial press.

The RF component industry therefore has some significant investment challenges ahead and the industry is unlikely to be in a position to finance developments for markets with unproven unestablished volume potential.

Is there enough present and future profit in the RF component industry to sustain present and future device innovation? This depends on future volume and price expectations.

Skyworks for example announced a doubling of earnings in November 2007 and attributed this achievement to the higher ASP's achieved in 3 G phones compared to 2G GSM.

To quote from the earnings statement

' Compared to $1-2 dollars for 2G(CDMA and GSM), the average selling process (ASP's) for front end content in multi mode handsets is three times bigger (nearly $6 dollars). This represents an incremental opportunity of billions of dollars'

This may be true but the counter argument remains that handset vendors expect the RF BOM to be no more than 7% of the total BOM of the handset[54]

Additionally they might be expected to anticipate LTE handsets moving down towards present GSM cost levels certainly within the three to five year time scales being discussed in the context of LTE 800 handsets.

In low tier phones this implies a total BOM for an entry level product of 30 dollars and an RF BOM of $2.1 dollars which after multiple PA's have been accommodated does not leave much budget or ROI recovery opportunity for duplexers, adaptive matching components and or innovative digital duplexing solutions.

This in itself may be an argument for half duplex but the argument would only be valid if all UMTS and LTE phones were half duplex.

They may actually be some merit in this but we detect minimal enthusiasm for this suggestion either in the handset or component vendor community.

We would assert that R and D investment will only be committed to LTE 800 handset development if and only if there is a strong RF architectural commonality between LTE 800 and LTE 900 handsets.

Making LTE 800 handsets half duplex would increase rather than decrease the present distance/difference between LTE 800 and LTE 900 handsets.

The difference could be lessened if LTE900 handsets were made half duplex but we are not aware that this has been considered or seriously studied. If LTE 900 handsets were made half duplex then there would be a rationale for making all LTE handsets in all bands half duplex.

In practice as things stand at the moment, the device innovation needed to bring half duplex handsets to market will move more slowly than vendor statements would presently suggest. If the market is confined to European LTE 800 and if this market remains spectrally fragmented then innovation will be particularly slow.

This has a number of implications. It means that band harmonisation remains an important imperative. Country specific iterations of regional band plans are particularly problematic. Software radio solutions, particularly software radio solutions optimised for a relatively small market by value and volume will be slow to appear and/or may never appear.

[54] Based on industry inputs to the RF Cost Economics study.

Making LTE800 half duplex does not make things easier for the component vendor community. Arguably in some areas, for example power amplifiers, the design task becomes more complex and more at odds with mainstream (full duplex) FDD design requirements.

There is some relaxation in TX filter requirement but little or no relaxation in RX filter requirements and some other specifications become more onerous. For example an RX/TX switch optimised for low harmonics needs to be added in to an already complex multi throw switch path.

This combination of technical and commercial imperatives would therefore suggest that even if half duplex can be justified on the basis of band flexibility it will be hard to justify in terms of commercial return if that return has to be realised uniquely from LTE 800 in Europe and particularly hard to justify on an individual country by country basis.

9) Summary

9.1 How would a UK-specific terminal rate in terms of priority for product development for the key vendors?

Very low, we could detect only minimal enthusiasm for a European specific terminal so a UK specific terminal would be more or less inconceivable

9.2 What would be the impact on cost for the market size given that only a limited amount of spectrum is available under Ofcom's current proposals?

The market volumes implied by a UK only handset design iteration would suggest additional costs would need to be recovered in the order of several tens and possibly several hundred dollars per phone. The RF Cost Economics Study quantifies these costs in more detail.

9.3 How would the vendors perceive a one-country national band plan that was dependent on half duplex to provide the flexibility?

They would perceive half duplex as being an additional incremental design task the cost of which would need to be amortised over limited market volumes.

9.4 How long would it take for terminals to be developed, given that under Ofcom's current proposals the band plan (assuming any mobile operator has been successful in obtaining spectrum) will not be known until the outcome of the auction?

There seems little prospect that terminals would be developed for this market.

9.*5 Does half duplex provide a* ***cost effective*** *option for delivering channel plan flexibility in the band?*

No as it is dependent on the R and D non recurring engineering costs likely to be incurred as a result of needing to develop half duplex handsets and the market volumes over which these costs can be amortised. The market volumes, R and D and opportunity costs associated with half duplex suggest that the option will not be cost effective from an overall industry perspective on a European wide basis. It would be even less cost effective for a UK specific implementation. In terms of possible cost savings, the consensus view is that handsets will need to support FDD for some markets and there will therefore be no cost saving. If additional research and development and non recurring engineering expenditure has to be amortised, the handsets will cost more.

9.6 Will the performance of half duplex handsets be better or worse than full FDD handsets? If so by how much?

Under certain conditions there may be a performance benefit on the TX path due to the relaxed filtering requirement of the order of 2 to 3 dB but this would hardly ever occur in practice.

9.7 Will the industry be willing to develop these handsets?

From the responses we have received we would say this is doubtful. If all LTE handsets in all bands were half duplex it would be easier to justify but the merits/demerits of half duplex in other bands have presently not been investigated to an adequate level of detail.

9.8 Will the industry have the technical and financial resources needed to develop and manufacture these handsets at the required time at the required volume?

This is doubtful. Present price pressures suggest the RF BOM ASP in a 2012 LTE800 handset will provide a poor ROI for the required technical and commercial investment.

9.9 Will there be sufficient component multi sourcing to meet cost and performance expectations?

This depends on the future viability of some of the 'new players' in the RF device space. Companies like Epcos, Avago and RFMD, Triquint and Skyworks are well established and have relatively broad revenue streams.

Some of the new players like Wispry and Peregrine need to meet investment expectations that can be hard to reconcile with present industry adoption time scales and component margins.

Others such as Paratek have high value business from non cellular (military and public safety) customers. All of the above have stringent ROI requirements that are unlikely to be met by the LTE 800 half duplex handset market.

9.10 Does half duplex remove or lessen the need for spectral harmonisation?

Theoretically yes, in practice no due to the present and likely future commercial dynamics of the industry.

LTE 800 would be easier to justify commercially if universally deployed into all other LTE bands but there would have to be compelling evidence of system gains for this to be justifiable.

If legacy full duplex UMTS (and therefore by implication full duplex LTE) has to be supported as well as half duplex LTE then this would imply additional standardisation work the cost of which would need to be recovered, additional R and D the cost of which would need to be recovered and additional component cost in the handset (assuming a need for separately optimised half duplex and full duplex switch and routing paths).

In practice the RF component vendors, transceiver vendors and handset manufacturers who have contributed to this study are sceptical of the technical merits and commercial viability of implementing half duplex FDD specifically for the European 800 band. Although half duplex is perceived as being easier to implement than full duplex it still represents additional design work if full duplex needs to be supported in the same handset in the same band. These reservations would be amplified if a UK specific iteration were to go forward.

The only possible motivation would be to achieve economies of scale in terms of LTE 800 handset sales into Europe (a 'universal' European LTE handset) but this would only be realised if **all** handsets were half duplex. If full duplex also needs to be supported for some markets then this justification disappears.

Finally there may be other (RF MEMS based) innovations that in the longer term make country to country variations in a band plan easier to support technically and commercially without incurring some of the standardisation work, development work and system performance issues implicit in half duplex FDD.

The lack of certainty in terms of the time scale of availability of these devices suggest it would be imprudent to base band plan allocation policy on these possible future solutions.

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