Half duplex/full duplex LTE 800 handsets

A study for the GSM Association Spectrum Management Group on the RF cost and performance implications of supporting half duplex FDD for LTE 800 in Europe

Researched and written by **RTT** with market data from **The Mobile World.**

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Executive summary
The objective of this study is to test whether a half duplex FDD option for LTE 800 provides a technically and commercially viable and/or attractive solution to the present lack of spectral harmonisation in the European LTE 800 band.

This has involved gathering industry inputs on a complex and inter related mix of technical and commercial metrics based both on present experience and estimates of changes that will occur between now and 2012 when the first LTE 800 networks are expected to be deployed.

As you might expect there are a range of industry opinions at strategic level – for example issues of scale and supply chain economics.

There are a range of opinions at component level – for example what will oscillator noise floors be in 2012, the typical Q and insertion loss of a SAW or FBAR filter in 2012, the impact of other RF component technology innovations, for example RF MEMS, on device cost, size and performance.

There are a range of opinions on likely operational conditions – for example the received signal strength of DTV, user to user distribution statistics, TX power levels, user duty cycles and traffic symmetry/asymmetry.

Depending on the weighting given to these opinions and assumptions it is possible to prove that half duplex FDD delivers band flexibility benefits, cost benefits and performance benefits.

It is also possible to prove that any band flexibility benefits will in practice be hard to realise and that half duplex handsets will cost more and perform less well than full duplex handsets.

The truth may of course be somewhere in between and suggests a complicated answer to a simple question.

There is however a consensus particularly from respondents from the RF component community, transceiver and handset vendors that half duplex FDD LTE 800 will be hard to justify unless more universally adopted in other LTE bands. For instance half duplex might deliver some performance benefits for LTE/GSM handsets at 900/1800 MHz, 2600 MHz and/or for LTE 850 and LTE 700.

It is likely that additional research will be needed on this. Some of the findings in this study may be potentially relevant to this research.

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 in Appendix 2 was provided by our colleagues at The Mobile World.

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1) 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 how 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.[1]

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.

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.

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[1] 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. These effects are quantified in Appendix 2.

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

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 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. These differences are quantified in Appendix 1.

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 likely Release 9. However the work would be given a lower priority than present full duplex and TDD work items.[2] This view has been corroborated from other industry sources.[3]

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.[4]

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[2] **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. So leave it as a business decision by the operator and vendors which way they want it.

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.**

[3] **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.

[4] **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 so "come hell or high water" *I am confident* that it will be December! 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 very 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.

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.

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 time scales. Component vendors will not commit development resources until these standards issues are resolved.[5]

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.

So back to base camp. Will half duplex FDD help meet the specific needs of the European band plan? Does half duplex provide a **cost effective** option for delivering channel plan flexibility in the band? Will these handsets cost less or more than equivalent full FDD handsets and by how much? Will their performance be better or worse than full FDD handsets and by how much? Does the band plan (channel raster, duplex spacing and operational bandwidth) make any difference to the half duplex/full duplex decision? Will the industry be willing to develop these handsets? Will the industry have the technical and financial resources needed to develop and manufacture these handsets at the required time at the required volume? Will there be sufficient component multi sourcing to meet cost and performance expectations? Does half duplex remove or lessen the need for spectral harmonisation in the LTE 800 band plan?

As a general comment it has to be stated that just because something can be done and should be done does not mean it will be done.

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). We discuss and quantify these reasons below.

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. This developing difference will dominate the allocation of engineering and investment resource. [6]

2) Arguments for and against half duplex

Let us assume there are seven separate band plans needed in an FDD LTE 800 European handset.

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

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[5] Comment from European 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:

- o the first few movers are forced to wait (product availability is delayed beyond the 2/3 years implied above);
- o 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;
- o markets that decide after that time will miss the boat if they choose a band / plan that is 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?

[6] Relative market sizes are quantified in Appendix 2.

Let us assume the seven band plans are substantially as shown below in Figure 1 (chart reproduced from Page 8 of the ECC PT1 meeting 14/16 May 08 GSMA submission document).

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

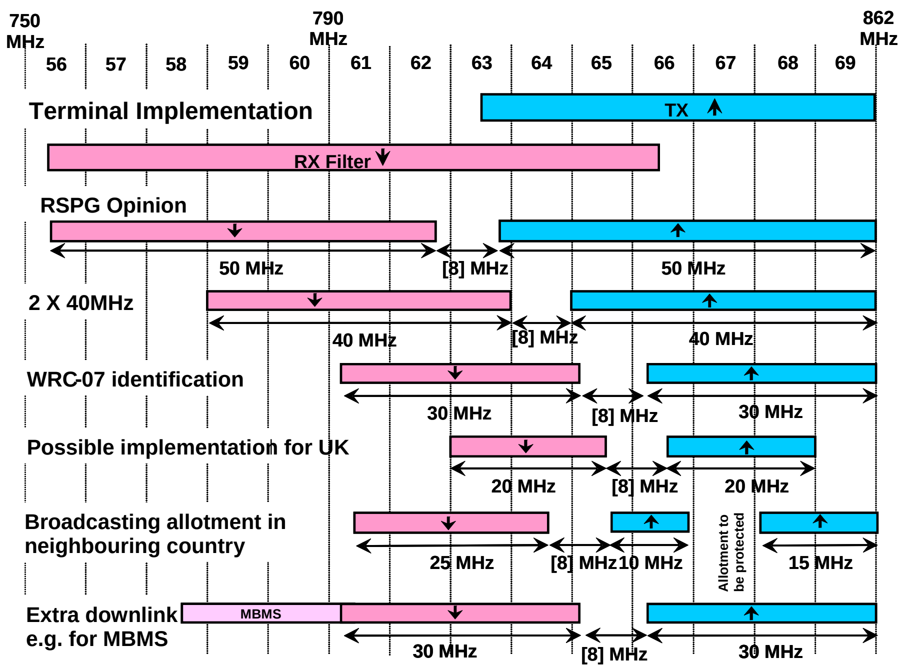
If all options were half duplex FDD then it would not theoretically matter where the duplex gap was placed.

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

In order to validate these options we need to examine the performance of all other options first assuming full duplex and then comparing this with a half duplex implementation both in terms of cost and performance.

Figure 1 shows a range of theoretical band plans that have either been discussed previously or could be possible in the future.[7]

Figure 1 Possible Band Plans for an LTE 800 handset for Europe



The above band plans 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 F then A (two by 50 MHz), B (two by 40 MHz) and E (25, 10 and 15) are 'unique' band plans each requiring their own duplexer. C, (30 by 30) D (20 by 20) and possibly E (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.[8]

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[7] Original figure included in Page 8 of the ECC PT1 meeting 14th/16th May 08 GSMA submission with subsequent amendments.

[8] 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

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.[9] 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.[10]

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 in Appendix 1 suggest that an RX filter would be needed for each band.[11] 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.

The bandwidth calculations (Appendix 1) 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.[12]

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.

As the calculations in Appendix 1 show, 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

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sources. For wider bandwidths there will be a requirement for additional external components unless a performance compromise is accepted.

[9] Estimates from Avago 16th June 2008

[10] 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

[11] 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.

[12] These effects were quantified in the previous half duplex study.

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. The effects of this are quantified in Appendix 1.

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 (see appendix 3) 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, 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.

3) Appendix 1 – Technical analysis

Introduction

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.[13]

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.

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.[14]

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

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[13] 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.

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

LTE handsets therefore have similar[15] 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.

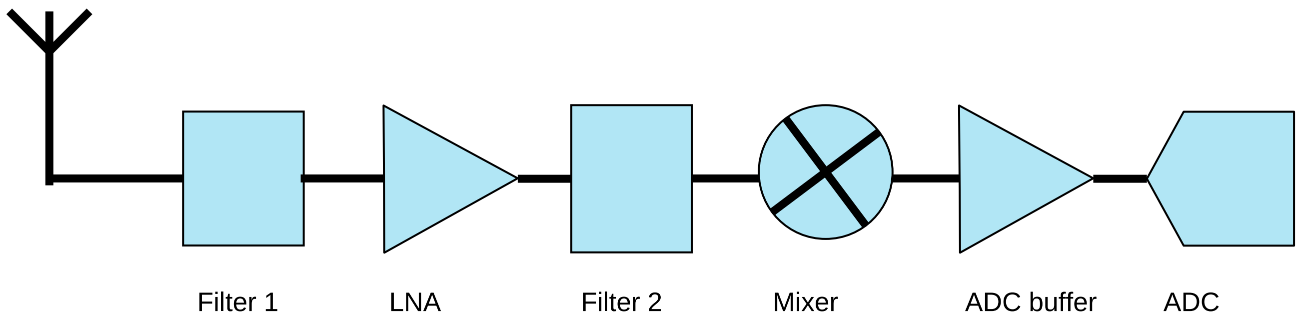
The motivation of introducing half duplex into the LTE800 band is primarily to help resolve European band planning issues. It allows different countries to deploy different duplex spacing, to move the position of the duplex gap, potentially reduce the duplex gap and in some cases eradicate the duplex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

The LTE 800 band is being 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



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. [16]

[15] Anecdotal experience suggests the specification for LTE is about 1 dB tougher than UMTS.
[16] 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.

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

Calculations[18] 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.[19] 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.

[17] We cover this in more detail in Appendix 4
[18] Qualcomm inputs to the ECC PT1 meeting 14th to 16th May 2008
[19] And the power and gain required from the amplifier

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).

The benchmark for the comparison is therefore the cost and performance of a standard full duplex LTE 800 terminal implemented between 790 and 862 MHz with an 8, 10 or 12 MHz duplex gap and 5 or 8 MHz raster.

This will be compared with the cost and performance of a terminal with two by 30 MHz, two by 40 MHz and two by 50 MHz operational bandwidths implemented as full FDD and half duplex FDD.

The impact of the above of a 5 or 8 MHz channel raster and 8, 10 or 12 MHz duplex gap on these options will be quantified.

The terminal to terminal interference when working in half duplex mode for two handsets at 1, 2.5 and 5 metres apart will be quantified. Note additional handsets within the same radius will add to the unwanted signal energy.

All of the above options will be compared in terms of cost and complexity including relative DC power drain profiles.

Receiver Type

The assumption is that due to the commercial requirements of providing low-cost, low form factor, multi-standard, multi-band terminals, direct conversion (zero or near zero IF) technology will be the architecture of choice for the receiver (and probably the transmitter). The direct conversion (DCR) architecture optimised with correct circuit design procedures allows a highly integrated terminal implementation meeting most of the design targets.

Sensitivity and large signal handling capability are the 'top and bottom' of the receiver dynamic range.

Sensitivity is largely a function of the circuit techniques and design choices made at the front end of the receiver. It is one of the key parameters to be met in meeting system performance requirements. Essentially sensitivity determines range (coverage), selectivity determines capacity.

In order to dimension the large signal handling requirements of the receiver it is necessary to consider the sources and strengths of signals (wanted and unwanted) to which the receiver will be exposed.

As these parameters are strongly related it is an iterative process to determine the overall receiver performance.

Receiver Sensitivity and Dynamic Range

Receiver sensitivity requires that the signal to be received has a defined Carrier-to-Noise Ratio (CNR) at the input to the demodulator. The required CNR value results from the demodulated quality (Bit Error Rate (BER)) and the effect that the demodulation process has (loss or gain) on the signal. The noise referred to in the expression CNR is the noise level, or floor that the signal to be demodulated 'sits on'. The noise will fill the available bandwidth and so the noise energy is also a function of this bandwidth.

In a well designed receiver, the noise floor is the result of the front-end processing that the received signal undergoes. Losses include component interconnections and couplings, filters, interstage mismatches and individual component losses. Gains come from the active stages e.g. low noise amplifiers (LNA), mixers and buffers.

The result of these losses and gains are expressed in Friis formula: where F_{TOT} is the total noise produced

$$F_{TOT} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 \times G} + \bullet\bullet\bullet$$

by the front end of the receiver, Fx is the noise contribution (factor) from each stage and G_x is the loss or gain from each stage. It is the terms in formula that determine the main performance specification for the whole receiver.

F_1 is the first stage in the chain i.e. the losses of the front-end filter(s), this directly degrades the receiver sensitivity. G_1 is the 'gain' (loss) of the first stage i.e. the filter(s) also acting on the second term to further degrade the noise factor. Hence the importance of low loss filters.

The third (and subsequent) term contains G, which is the gain for the next stage i.e. the LNA. This has a positive gain and serves to lift the received signal above the noise floor: thus, being on the bottom line of the formula reduces the noise contribution of the following stages. The gain of the next stage, usually the mixer, reduces still further.

The temptation is to use a high LNA gain to obtain a minimum noise figure for the receiver and hence high sensitivity. However, it must be considered that the higher the gain of the LNA, the larger the signal passed on to the mixer! This will require the mixer to have a very large signal handling capability which will in turn produce extra noise due to the higher current drawn. It will also flatten the battery faster. Similarly, this larger signal will be passed on through subsequent stages that will also need to have this large dynamic range performance.

The designer has the task of 'balancing' these parameters given the availability of suitable components, for example filters, LNAs, mixers, matching components and circuits to obtain acceptable sensitivity and dynamic range.

Interstage matching continues to be an important part of the design process. For most interstage couplings in the receiver and especially in the transmitter, power efficiency is the main consideration i.e. the ability to transfer signal energy from one stage to the next with a minimum of loss.

However, in the front-end of the receiver, low noise performance is the key consideration. To ensure the LNA generates as little noise as possible the input matching circuit is dimensioned not to be as power efficient as possible but to ensure that the LNA is in conditions of lowest noise generation. If this condition can be achieved the receiver will be at the point of best performance.

The optimum values for noise matching vary according to frequency, bandwidth and circuit loading. New MEMs technologies are being introduced that have the ability to vary the conditions of a matching circuit by means of DC control voltages. This means that as different portions of the band are used the matching can be varied to maintain optimum performance. It also gives the opportunity to utilise a wider bandwidth from the LNA. This may reduce the number of LNAs.

Although the ability to optimise matching can be provided, a challenge is to be able to measure a parameter that gives information as to how much and in which direction to make component value adjustments. It is usual, because it is easier, to measure/analyse signals at baseband and then to use an algorithm to create a control signal to adjust the matching. It is important using this technique to ensure that the measured parameter is a true reflection of what is happening as a result of varying the matching, and is not influenced by any other parameter.[20]

The noise in the baseband signal to be analysed is a product of the receiver front signal circuits and the noise contributed by the down converting local oscillator(s) - LO. The LO noise therefore must be insignificant compared with the RF front-end noise. Again very high Q MEMs component techniques for example FBAR resonators are now making very low noise oscillators practical.[21]

The terminal designer has a choice of how the improvement in oscillator noise is applied. For instance, consider the receiver Local Oscillator (LO). The 'frequency swing' of the oscillator determines the receiver bandwidth that can be covered e.g. 30, 40 or 50MHz. If the 'frequency swing' of the oscillator is maintained at its previous range then the lower noise will give improved receiver sensitivity (for FDD or HD).

However, if the previous oscillator noise (i.e. higher) was acceptable and hence the receiver had sufficient sensitivity the benefit of the new lower noise oscillator may be taken to design a wider oscillator swing i.e. a

[20] Noise matching networks have loss and so any improvements from tuning need to provide a net overall gain in performance.
[21] http://www.paper.edu.cn/download_feature_paper.php?serial_number=Verigy2007-017

http://www.hfoscillators.com/apskhanna/articles/IMS2003.pdf wider receiver tuning range, at the original noise level, maintaining the original receiver sensitivity but with an increased bandwidth.

Receiver Interference Summary.

In FDD Mode:

1) Strongest interferer is own transmitter channel frequency/power. Two mechanisms must be considered.

The transmitter outputs an 'on channel' signal power of +23dBm. The receiver input duplex filter(s) must attenuate this down to a level acceptable to the receiver dynamic range. The filter roll-off rate and attenuation determine the minimum duplex spacing that can be used.[22]

The transmitter will also output broadband noise extending out to the receive channel frequency. This noise will add to the noise floor at the receiver input and thus degrade the sensitivity. This wideband noise must be prevented from appearing at the final output of the transmitter (the antenna) by low noise design techniques and filtering of any residual noise that remains.

The insertion loss of the required filter(s) at the receiver input will directly detract from the receiver sensitivity.[23] Similarly filters inserted in the transmitter output will degrade the transmitter efficiency.

2) Geographically adjacent terminal transmitter on its lowest channel frequency when the 'victim' receiver is on its highest channel frequency.

The free space propagation loss at the transmit frequency (at a defined separation distance i.e. 1metre) together with the receiver dynamic range will define the minimum duplex gap.

3) Received DTV signal strengths together with receiver dynamic range and receiver input filter(s) roll-off rate determine receiver band edge frequencies.

In HDD Mode:

1) Assuming overlapping terminal receive/transmit bands then geographically adjacent terminal transmitters may be on the victim's receiver channel. The only protection is a receiver dynamic range sufficient to handle this occurrence.

2) Received DTV signal strengths together with receiver dynamic range and receiver input filter(s) roll-off rate determine receiver band edge frequencies.

FDD

'Own Transmitter' to Receiver Interference

Working in FDD mode the strongest potentially interfering signal is the terminals own transmitter power (+23dBm). This is a duplex split away and determines the filter(s) performance required in the receiver front-end. The filter will be required to attenuate the transmitter power that is within the dynamic range of the receiver.

Investigating the performance of current state-of-the-art ICs for UHF portable terminal applications gave a very close similarity of the RF parameters relevant to this study.

For example.

Cascaded gain (LNA + Mixer)   25 – 16dB depending on AGC setting

Noise figure   2.1 – 6dB

[22] Other factors affecting the duplex spacing include variation in filter performance with temperature and manufacturing tolerance.
[23] You can only filter the PA noise in the RX band at the output of the PA. Those on the RX side are primarily for blocking.

Input IP_3 -5 - +2dBm

These figures give a start point for the transmitted power attenuation calculations:

The potentially greatest impact of transmitter energy is when the receiver is attempting to recover a low level signal i.e. at condition of highest gain,

Cascaded gain		25dB
Noise figure		2.1dB
Input IP_3		-5dBm

It is usual to consider the 1dB compression point to be approximately 10dB below the IP_3 figure

1dB compression point -15dBm

It is necessary to decide the maximum signal level allowed at the LNA input to ensure that any inter modulation products that are produced are at an acceptably low level.

A customary 'rule of thumb' is to restrict the maximum LNA input to 6 dB below the 1 dB compression point.

Maximum LNA input -21 dBm

The next step is part of an iterative process, trading the filter insertion loss (IL) against the stop band attenuation at a distance equal to the duplex spacing.

Assume filter IL		4dB
∴ Maximum input	-16 +4	-17dBm
Transmitter output		+23dBm
∴ Required attenuation	23 – (-17)	40dB at a duplex spacing distance

The transmit section of the duplex filter can now be derived.

It will be necessary to prevent noise generated by the transmitter, at the receive frequency, from reaching the receiver. How much noise is generated in the transmitter and by how much must this be attenuated?

The industry standard noise reference is defined at 17 deg C, using Boltzmann's constant and in a 1Hz bandwidth i.e. –174dBm/Hz. So, to derive the actual noise floor this value must be 'bandwidth adjusted'. In a 5MHz raster system the effective bandwidth process in the receiver will be 3.84MHz.

N_p	=	$10\log_{10}3.84$(MHz)dB
	=	66dB
So terminal noise floor (bandwidth adjusted)	=	-174 + 66
	=	-108dBm

Assuming a 5dB noise figure for the receiver

Total reference noise floor (RNF) = -103dBm

This figures sets the 'base' for the C/N hence sensitivity, if it is compromised by the wideband transmitter noise (Tx int), the sensitivity will be degraded.

Sensitivity Reduction (SR) $= 10.\log_{10}(1 + 10^{(\text{Tx int} - \text{RNF})/10})$

For a sensitivity reduction of 0.1dB, in a 3.84MHz bandwidth and a reference noise floor of –103dBm

Tx int = $10\log_{10}(10^{SR/10} - 1)$ + RNF dBm

= -119.5 dBm

So Tx output noise power at the Rx frequency must not be greater than –119.5dBm

The Tx wideband output noise must now be dimensioned.

VCO phase noise at a duplex offset will be attenuated by a filter (typically SAW) before the transmitter Power Amplifier (PA), so a low figure maybe assumed i.e. –164dBm/Hz

PA + modulator noise contribution = 8dB (ref ADI Othello chip set)

Tx power = +23dBm

Therefore Tx output noise power at Rx frequency = -164 + 23 + 8

= -133dBm/Hz

= -67.2dBm in a 3.84MHz B/W

Therefore the required Tx to Rx duplex isolation = 119.5 – 67.2

≅ 53dB

'Geographically Adjacent' Terminal to Terminal Interference

Signals from geographically adjacent terminals may interact when one terminal is transmitting whilst the adjacent terminal is receiving. The worst case will be when a terminal transmitter is on its lowest channel frequency adjacent to a terminal simultaneously receiving on its highest channel frequency. The necessary duplex filter response and accordingly the minimum duplex gap may be calculated.

Assuming a 50MHz bandwidth TX channel 862 – 812MHz then frequency of interest is 812MHz as free space attenuation (loss) is lowest at this frequency.

Using $L_{dB} = 32 + 20\log f_{MHz} + 20\log d_{km}$:

Free space propagation loss at a T-to-T distance of 5metre = 44.2dB

Free space propagation loss at a T-to-T distance of 2.5metre = 38.2dB

Free space propagation loss at a T-to-T distance of 1metre = 30.2dB

+23dBm transmission power

Received signal strength at 5metre = -21.2dBm

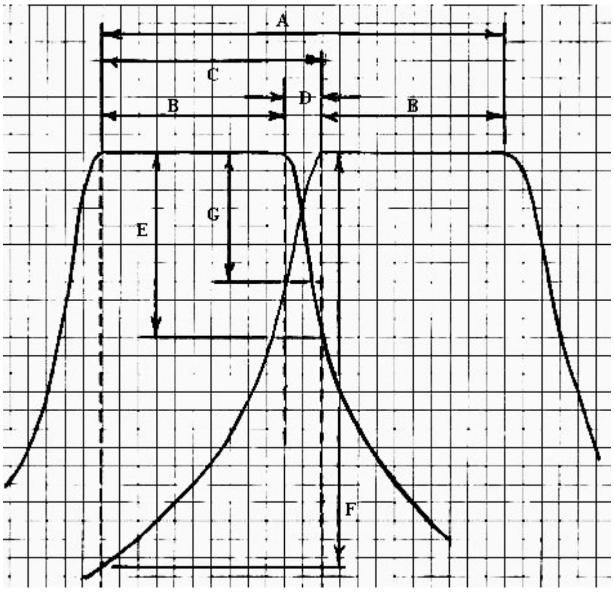
Received signal strength at 2.5metre = -15.2dBm

Received signal strength at 1metre = -7.2dBm

As we have previously calculated the receiver can accept a maximum signal input level of –17dBm. However, we have shown that it may be exposed to a signal level of –7.2dBm. It is therefore a requirement of the receive section of the duplex filter that it provides an attenuation of at least –17 – 7.2dB i.e. 9.8dB a duplex gap away.

The requirements of the duplex derived in the previous calculations may be tabulated:

Figure 3 Filter bandwidth characterisation



Where:

A	=	Band Occupancy (required antenna bandwidth)	
B	=	Rx & Tx Channel Bandwidth	
C	=	Duplex Split	
D	=	Duplex Gap	
E	=	Duplex filter Rx section attenuation at duplex separation	40dB
F	=	Duplex filter Tx section attenuation at duplex separation	
	=	53dB for a 5MHz channel raster	
	=	47dB for a 10MHz channel raster	
	=	41dB for a 20MHz channel raster	
G	=	Duplex filter Rx section attenuation at lowest Tx channel	9.8dB

Note: the attenuation figure of 40dB for E and 9.8dB for G (within +/- 0.1dB) is the same for all cases of channel bandwidth (30, 40 & 50MHz) and duplex gap (8, 10,12MHz). Only the point on the filter characteristic at which this attenuation is required will vary.

The figure for F is calculated with respect to receiver sensitivity and this varies with channel raster (5, 10 or 20MHz).

In all cases calculations are based on a TX power of +23dBm

30MHz channel bandwidth & 8MHz duplex gap, then:

A	=	68MHz 8.2%	band occupancy	
B	=	30MHz 3.5%	Tx & Rx bandwidth	
C	=	38MHz	duplex split	
D	=	8MHz	1%	duplex gap
E	=	40dB attenuation over Rx section through the TX band		

F	=	53dB attenuation in the Tx section through the Rx band for a 5MHz channel raster		
	=	47dB attenuation in the Tx section through the Rx band for a 10MHz channel raster		
	=	41dB attenuation in the Tx section through the Rx band for a 20MHz channel raster		
G	=	13dB attenuation in Rx section at lowest Tx frequency i.e. 832MHz		

For a 40MHz channel bandwidth

A	=	88MHz 10.8%	band occupancy	
B	=	40MHz 4.8%	Tx & Rx bandwidth	
C	=	48MHz	duplex split	
D	=	8MHz	1%	duplex gap

For E, F & G see the 30MHz figures above

For a 50MHz channel bandwidth

A	=	108MHz	13.4%	band occupancy
B	=	50MHz 6.0%	Tx & Rx bandwidth	
C	=	62MHz	duplex split	
D	=	8MHz	1%	duplex gap

For E, F & G see the 30MHz figures above

Also:

Working in FDD or HDD in reverse duplex mode the receiver will be spectrally adjacent to DTV signals. The typical strength of these may be calculated:

DTV Signal Strength:

Inputs from other GSMA related study work suggested that the received DTV signal strength (on channel) was typically –20dBm but that it could peak to 0dBm.

Given the FCC DTV transmitted power mask, extrapolation gave the actual signal power at the mobile band edge in order to dimension the receiver front-end filter requirements.

We have been quoted typically 100dBuV/m propagated signal strength for this study. Using this figure we can calculate what this means in terms of signal energy at the receiver input:

Field Strength (dBuV/m) =

Indicated Signal Level (dBuV) + Antenna Factor(dB) + Antenna Coupling Loss(dB)

Assuming an antenna gain of 0dB, an antenna coupling figure of 0.4dB and a field strength of 100dBuV/m the induced signal energy would be:

FS – AF – ACL

100 – 0 – 0.4 = 99.6dBuV

Converting to dBm:

99.6dBuV – 107dB = -7.4dBm - this agrees well with the inputs from other study work undertaken.

As the maximum receiver input has been calculated at –17dBm and a typical DTV field strength at the receive antenna is estimated to be approximately –7dBm, the receive duplex filter must provide an attenuation of at least 10dB at any anticipated DTV channel frequency.

Note the antenna coupling figure of 0.4dB. This infers the use of adjustable (optimised) MEMs impedance matching technology. Optimisation is, of course, designed to improve cellular receiver performance but does also allow the efficient coupling of unwanted signals into the receiver.

Summary

In Appendix 1 we have considered the prime factors that determine receiver and transmitter RF performance. We have considered the impact on these parameters of adopting either an FDD or an HD approach to LTE 800 terminal implementation.

Source information on which the calculations are based has been obtained after consultation with senior engineers and other technical managers tasked with developing components and terminals for LTE applications.

Inevitably certain information is not in the public domain and we have therefore used our knowledge of mobile terminal development trends to anticipate component technologies and parameters that will be available within the development timescales of LTE 800 terminals.

It is clear that RF filters and filtering techniques will play a major part in the realisation of multi-standard multi band terminals. New materials yield improved filter parameters for example lower insertion loss and narrower transition bands for wider bandwidth filters.

Newer integration and packaging techniques allow a wider application of filters supporting wider pass bands with lower ripple and offer closely characterised matching parameters over wider bandwidths.

However, it must be assumed that filter developments within LTE800 timescales are unlikely to produce any 'step-function' changes that would sweep-away present design approaches.

Wide ranging bandwidth and centre frequency variability is the goal of many current design programmes but it is extremely unlikely that these developments will benefit LTE800 within the first 3 to 5 years of initial network deployment (assumed as 2012).

Similarly, a parameter of concern is that of frequency variation with temperature – 20/25 ppm/Hz is currently the best available. Many papers are presented on techniques being experimented with, usually the addition of other chemical substances to the fundamental materials. However closer analysis of the results inevitably show a considerably degraded Q. This means band edges especially must be considered as varying with temperature over the LTE 800 development timescales considered in this report.

On the plus side, the ability to integrate lumped components with MEMs resonators that have a degree of variability will have considerable impact on the optimisation of current transmitter/receiver architectures and performance.

Matching, noise matching at the receiver input and efficiency matching at the transmitter output, have historically been a considerable compromise, especially at anything over 2 or 3 per cent bandwidth.

The variability now becoming available will offer considerably enhanced improvement of key parameters – 25% PA power saving and 3dB receive sensitivity improvement could be realised in next generation terminals over the specified LTE800 bandwidths.

To gain benefit from this matching process it is important that the matching estimation is separate for the transmitter from the receiver. For instance, although the antenna to be matched is common, the matching objective for the receiver and transmitter are quite different.

Especially in the case of FDD where the receive frequency is a distance away from the transmit frequency, it would be quite inaccurate to infer the receive input matching parameters from the transmitter output matching parameters.

In all RF filter technology the prime parameters are closely interactive. For instance, as bandwidth increases ($>$ 5%) it becomes increasingly difficult to realise a steep roll-off at band edges. This means to bring the LTE 800 receive band close (e.g. $<$ 1%) to DTV transmission channels becomes increasingly difficult.

Either the filter edges have to be made steeper by the addition of discrete components, or, the front-end active stages must have a higher large signal handling capability with the increased current and noise that this brings.

Similarly, unless counter-measures are taken, making a filter significantly wider, the middle of the pass-band 'sags' unacceptably, again needing discrete components to support it.

We have considered essentially three operational bandwidths (30, 40 and 50MHz) and three channel widths (5, 10 and 20MHz) with a possible requirement of 8MHz for compatibility with DVB-H). The factors defining these bandwidths should be summarised.

The three operational bandwidths are a definition of the bandwidth at the front-end of the receiver and the back-end of the transmitter. In the receiver the front-end filters, LNA, mixer(s) and buffers/coupling circuits must have 30/40/50MHz bandwidth regardless of channel bandwidth or raster. In the transmitter the back-end filters, PA and buffers/coupling circuits must be able to handle 30/40/50MHz bandwidths regardless of channel bandwidth or raster.

The channel bandwidths (5, 10, 20 & 8) are 'tuning' bandwidths. These are selected or tuned from the operational bandwidths. In the receiver they are selected further down the chain, and, given the increasing power of digital signal capability will certainly be selected in software processing or dedicated digital hardware. There is, therefore, the need to convert from the analogue domain to the digital domain. In the DCR this will be done at baseband (or near baseband) and will require a sampling process that meets the Nyquist criteria.

Power economic, i.e. portable terminal applicable, sampling Analogue-to-Digital converters have been developed extensively for WCDMA sampling and sub-sampling use (in first generation Superhet architectures and latterly in Direct Conversion architectures) and will be capable of handling the LTE 800 requirements.

Note that the terminal-to-terminal interference in the case of HD will require a greater Spurious Free Dynamic Range (SFDR) than the FDD case where the 'own transmitter' signal is less powerful.

In the FDD terminal the 'own transmitter' is the largest interfering signal source and with a 30MHz bandwidth channel, 12MHz duplex gap the required filter implementation is regarded as a simple task.

40MHz is more difficult with 50MHz a considerable challenge. Also, the attenuation band of wide bandwidth, steep roll-off filters turn back up again further out and so usually require to be cascaded with a roofing filter to maintain adjacent and subsequent channel performance. These issues were studied in the previous half duplex study.

In the HD approach the use of a Low-Pass filter in the transmitter output to remove the need for a lossy duplex filter may be considered. However, discussion with filter manufacturers highlights the differences in implementing a bandpass filter as opposed to a high or low pass filter. The bandpass filter is a series of 'mechanically engineered' substrate constructions while the low/high pass filter is composed of individual inductors and capacitors having a larger form-factor, a higher cost and a 'softer' performance characteristic.

In conclusion: the HD or FDD terminal may be required to operate over 30, 32, 40 or 50MHz operational bandwidths with 5, 8, 10 or 20MHz channel spacing and 8 or 12MHz split.

HDD operation removes the need to employ the transmitter output filter that is used to attenuate the noise produced at the receive frequency. This would potentially save 2/3dB power loss but it is unlikely that the output filtering can be removed entirely and still meet the output spurious product suppression requirements. Similarly, adjacent receivers may be exposed to higher spurious products from neighbouring transmitters.

Also taking the opportunity to use tx/rx band overlap the geographically adjacent receiver must either be able to handle much higher powers or a method found to avoid them. For example victim receivers reporting a low CQI (channel quality indication) will be moved to another time slot or channel or band. Adoption of a TX output low pass filter may not give much simplification benefit as such filters are of a larger form factor, higher cost and softer response shape than equivalent bandpass filters.

Similarly, the receiver section of the duplex filter may be simplified as attenuation of 'own transmitter' power is not required. The above comments relating to adjacent terminal interference are also relevant.

FDD operation requires the use of a duplex filter which would be a low cost, small form factor, highly integrated component in the case of a 30MHz operational bandwidth but would require to be assisted with discrete components in the case of 40 or 50MHz operational channels. It does however; define more precisely the large signal levels to which the receiver may be exposed.

Increasing channel bandwidth (5 $\rightarrow$ 20MHz) presents similar design challenges to both HD and FDD systems. As the channel bandwidth increases so does the sample rate required from the ADCs and DACs. As these are implemented in CMOS the DC power taken is directly proportional to sample rate and so the power budget must be carefully evaluated as wider channel bandwidths are adopted.

The quantisation of gains, losses and interference parameters shows that the potential benefits of HD adoption will require design capability of the highest order, a comprehensive understanding of the system/network environment and the support of one or more advanced component vendors.

Adoption of FDD would present a lower risk (i.e. well understood) approach with availability of a wider choice of components from a wider range of vendors but with a reduced operational flexibility.

In summary
HD/FDD Differences

Receiver
Receive sensitivity is a function of receive bandwidth at demodulation and receiver total noise figure.

Receive bandwidth (effective) at demodulation is the same for both HD and FDD i.e. 3.84MHz for a 5MHz channel scaling to 15.2MHz for a 20MHz channel spacing.

So, potential HD/FDD differences may be assessed in the receive total noise figure.

The receive noise figure is very largely a function of receiver front performance. This is composed of all losses before the first gain stage (LNA), early inter stage losses and LNA/mixer noise figures. Therefore, differences in filter losses between HD and FDD implementation impact directly on sensitivity. Differences (HD to FDD) in large signal handling requirements i.e. dynamic range, also have an effect as larger dynamic range requires more current thus creating more noise.

As the receiver (HD or FDD) will require input filters

Adoption of HD removes the 'own transmitter power' filter requirement but still leaves the need for filter protection against DTV signal energy. FDD therefore includes the 'own transmitter power' filter requirement in addition to the DTV rejection. The front-end loss difference has been assessed by a cross section of filter vendors as typically 1dB in favour of HD.

The FDD receiver also requires a larger front-end dynamic range to handle the signals and interferers received which will generate additional noise – typically 1dB. However, depending on the degree of protection considered necessary against 'adjacent transmitter' power in the case of HD this difference may disappear.

30/32/40 or 50MHz bandwidths will have a similar effect on both HD and FDD with a desensitization increasing to approximately 1.5dB at 50MHz. This figure does also depend on RF switch performance.

Transmitter
It is suggested that removal of the duplex filter will have a considerable benefit (2/3dB) for HD operation. This is based on the adoption of a simple low-pass filter (LPF) matching the PA output to the antenna.

Filter manufacturers have highlighted the fact that the LPF would be constructed from effectively discrete elements and consequently the benefit would be typically 1.5dB.

Additionally the LPF would have a softer characteristic i.e. a wider transition band and less stop band rejection. This means that a greater amount of band-edge response would be needed to meet transmitter out of band spurious specifications – typically 2MHz has been suggested.

The need for good (low) TX *harmonic* performance in half duplex LTE
One advantage of half duplex is that the output filter can be removed. (See above) However this means that that there is no 'far distant' protection against second or third order products. This in turn demands good (low) harmonic performance from components in the TX chain including switch paths to avoid interference with other users. Effectively you are relying on free space loss (the distance between users) to replace the the filter function.

The need for good (low) TX *linearity* in full duplex LTE
In full duplex LTE, TX harmonics will get filtered out by the output filter. However good linearity is needed in order to prevent inter mod products that can appear in the in band receive channels within the handset.

Impact of dynamic range on power drain
Dynamic range is the key to receiving weak (distant) signals in the presence of strong (interfering) signals.

The system of Automatic Gain Control (AGC) in which the receiver front-end gain is reduced to prevent overload cannot be used in this situation as the weak, wanted signal would also be reduced in level to the point where its C/N meant that it was unrecoverable.

However, if a weak signal is being successfully recovered when there is no strong interferer it is inefficient to expend high current levels to produce a wide dynamic range.

So, the dynamic range is a variable controlled by the receiver. We have shown that closely adjacent terminals can create a situation of potential overload that does require the large signal handling capability.

Evaluating a selection of UHF band RF tuner ICs the 'cost' of increasing the dynamic range can be assessed. Typically to double the dynamic range (an increase of 3dB) the required DC power will increase by four times. The absolute power required for these devices was found to be in the order of 200/230mW.

All of the above represent typical design and performance considerations most of which are relatively subtle but all of which demand design and engineering effort.

The decision as to where this effort should be placed has to be considered in the context of a rapidly changing market in terms of global volume and value distribution. This is discussed in the following sections of the study.

4) Appendix 2- relative market volumes in 2012

Handset volume market comparisons in 2012, Europe, China, India, the US and related scale economy implications. Component vendor scale economy examples.

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.

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 4 compares net subscriber additions by region

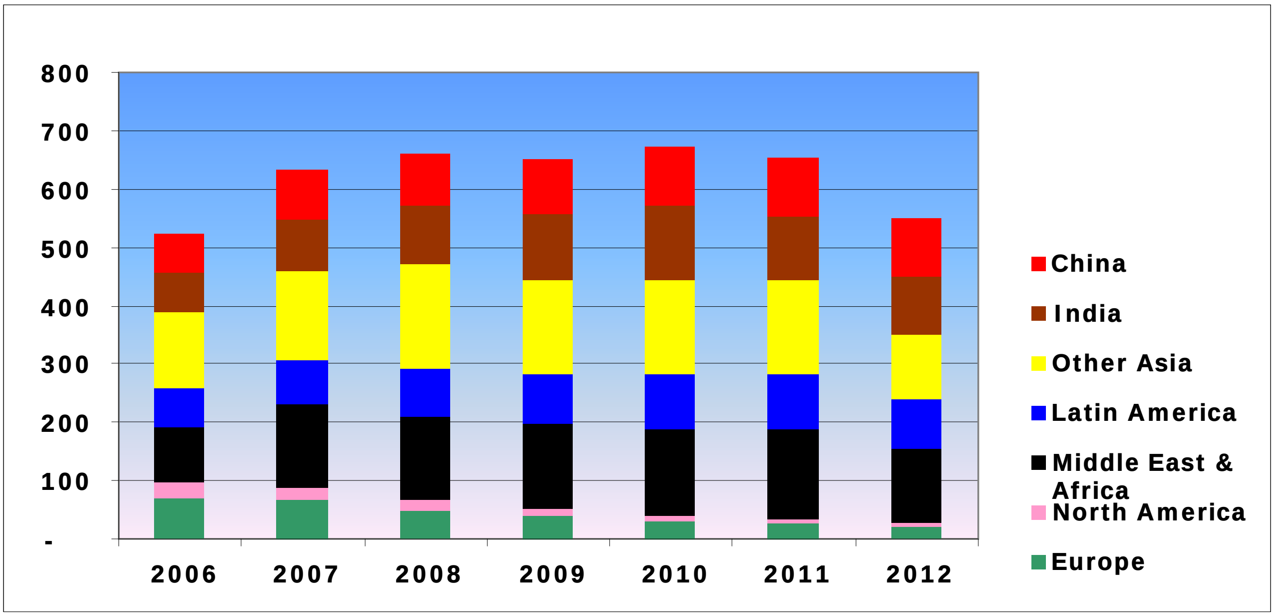
Figure 4 Table of Mobile Subscriber Growth (net additions) by region with percentage difference over 5 years, 2007 to 2012.

	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 5 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 6 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 7 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	

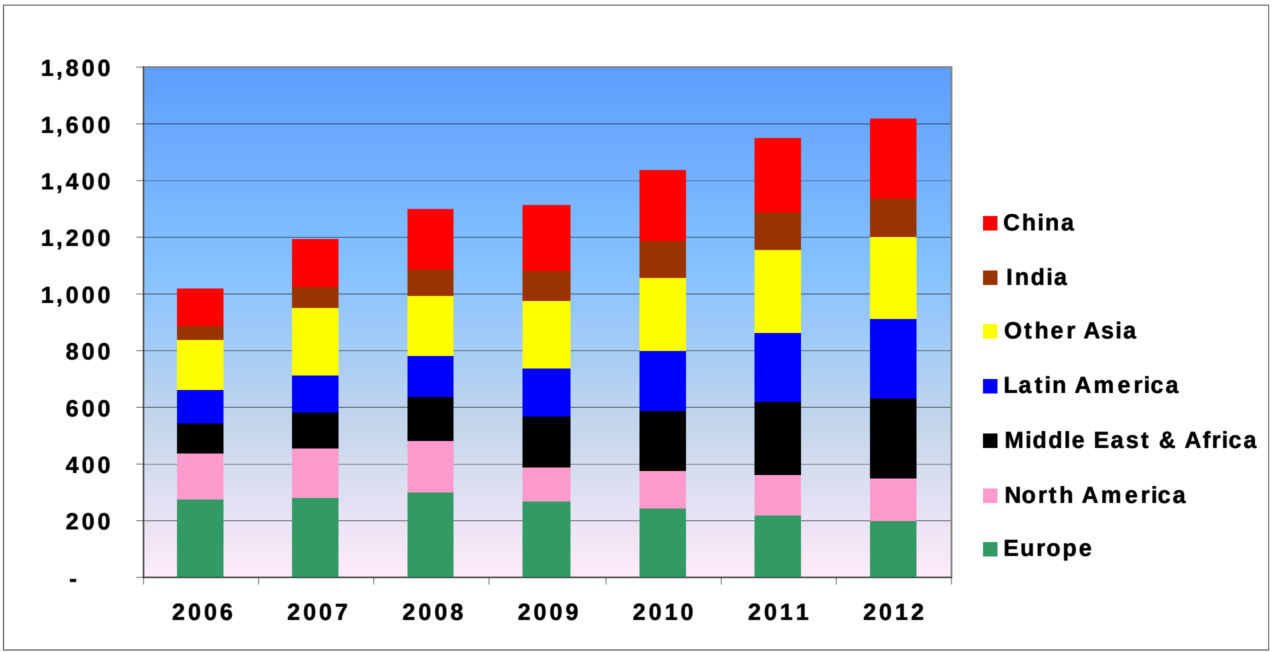
European market volumes are expected to decline from 284 million units to 191 million units over the five year period from 2007 to 2012 and reduced from 24% of the global market to 12%. Similarly, North America is expected to drop from 14% to 9%.

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.[24]

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 8. 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 8 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 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.

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[24] 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.

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.

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 Appendix 3 we reference a Press Release from Skyworks suggesting that they anticipate an increase in RF BOM value as the industry transitions from GSM handsets (with an RF BOM of just over two dollars) to 3G handsets with an RF BOM value of 6 dollars.

This does not accord with present market pricing trends.

The following are 'The Mobile World' calculated blended average selling prices for Nokia handsets (GSM and 3G) in Q1 2008[25] 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.

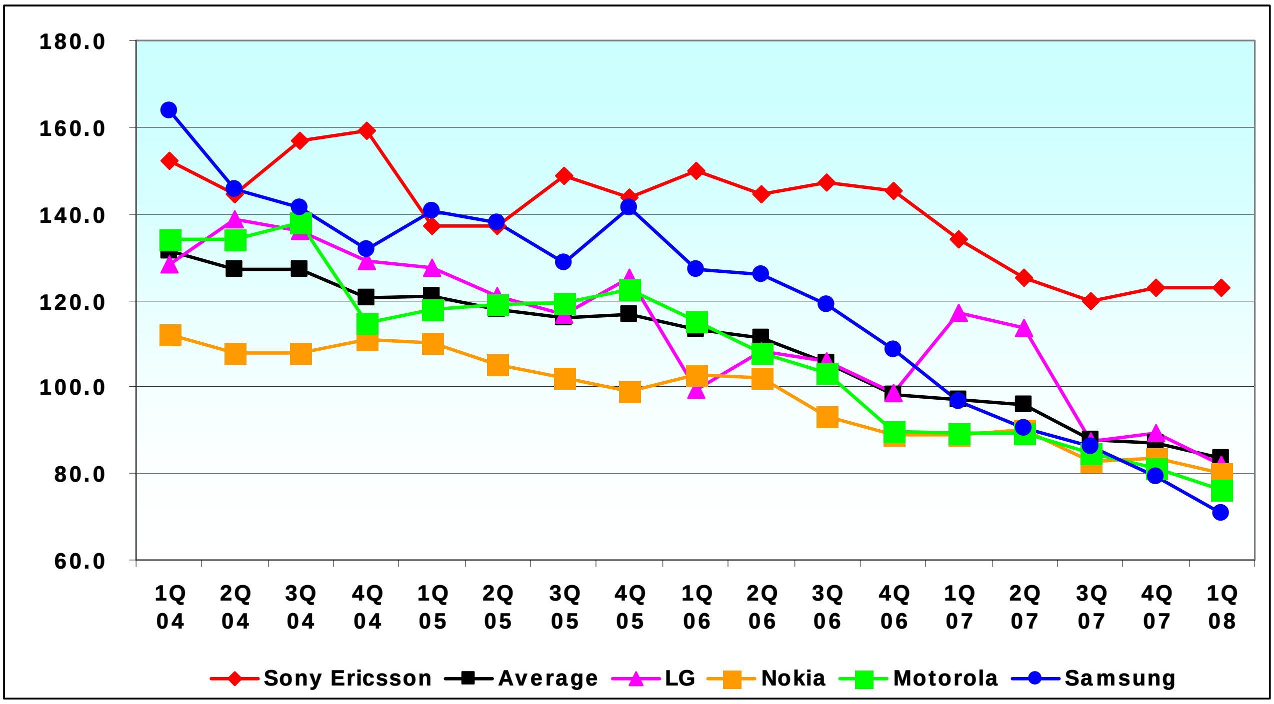
First the ASP's In Europe are double the ASP's in China.

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] 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.[26]

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. [27]

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 closer to two dollars rather than the 6 dollars anticipated by Skyworks.

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.

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.

[26] 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.

[27] 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.

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.[28]

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. [29]

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 Devices to deliver innovative integrated shielding and transceiver solutions to the market.[30] 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. At least the USA is now dominated by just two operators which makes life a little easier for RF component vendors.

5) Appendix 3 – Technical and commercial considerations

RF Device Performance trends now to 2012 .Related implications for the half duplex/full duplex decision process. The continuing need for harmonisation.

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[28] 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.

[29] 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.

[30] 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.

Questions to answer
Will RF MEMS provide enough flexibility to support multiple LTE800 band plans in Europe?

Do RF MEMS strengthen or weaken the case for half duplex LTE800?

Is the RF MEMS industry now sufficiently mature technically and commercially to become a mainstream part of the cellular handset RF BOM?

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. [31]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.[32]

The commercial merits and demerits of RF MEMS have been discussed in earlier studies[33] - 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.

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.

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.[34] 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).[35] 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.

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[31] Wispry claim this device will be used in a handset being introduced in 2009.
[32] 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.
[33] For example in the RF Cost economics study.
[34] Avago Press release 12th May 2008 Avago Wafer cap, industry's first semiconductor based chip scale packaging announcement.
[35] April 2008 Epcos Press Release

RF Micro Devices have stated similar ambitions.[36] Avago with a strong presence in power amplifiers, filters, duplexers, switches, diplexers and integrated front ends could also be an agent of industry consolidation.

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.[37]

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.[38]

Adaptive matching of the TX path is claimed to realise a 25% reduction in DC power drain[39] in conditions where a severe mismatch has occurred and can be corrected.

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.[40]

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.[41]

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.[42]

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. [43]

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

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[36] RDMD Press Release 21st February 08 Flexible RF front end for Bands 1,II, III,IV,V,VI,VIII and IX
[37] Epcos investor briefing May 6th 2008
[38] Peregrine 22nd May 2008
[39] Epcos press release as above
[40] Information from Peregrine 22nd May 2008
[41] A low noise oscillator is however expensive and current hungry.
[42] Peregrine 22nd May 2008
[43] 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.

(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.

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.

Figure11 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)

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.

These opinions are documented in Appendix 4 (summary of industry responses) but in essence half duplex does not seem to make the prospect of developing LTE 800 handsets for Europe any more attractive rather it makes it less attractive.

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[44] 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.

This is 11.6% of the centre frequency, [45] 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.[46]

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.[47]

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'[48]

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[44] RF MD Product announcement 5th December 2007

[45] 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%.

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

[47] 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.

[48] 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.

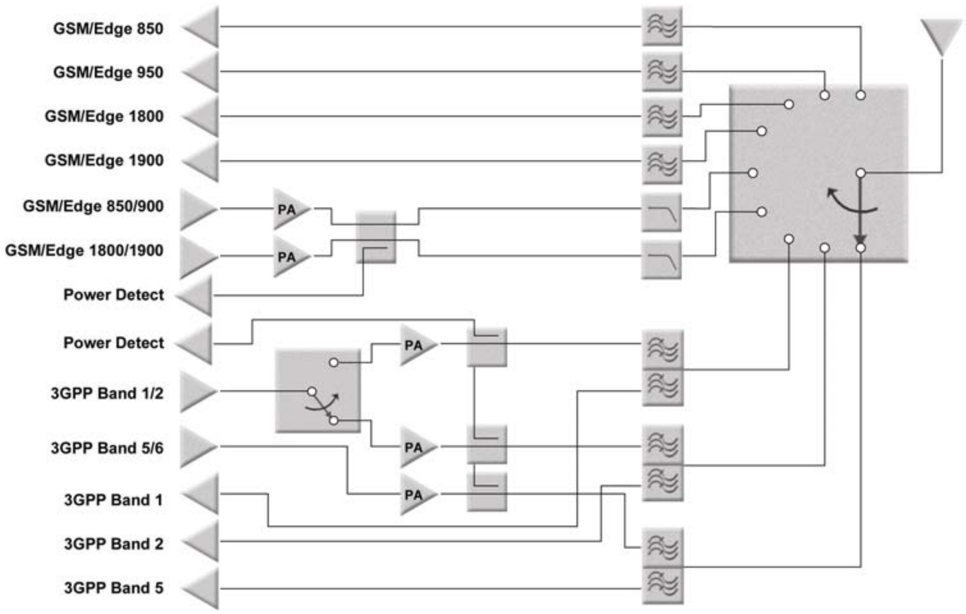
Such techniques and their successful implementation, whenever that may be, will generally be welcomed by the handset vendor community. However, as stated above, half duplex implies power amplifiers whose behaviour and performance will be sufficiently different from full duplex to imply an additional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

Path Switching for LTE800 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 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).[49]

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 much 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).

[49] 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.

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.[50]

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

Is there enough profit in the RF BOM to sustain this sort of development?
This returns us to our running narrative originally explored in Appendix 2 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.[51] 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.

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.

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

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[52]

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. 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.

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 very hard to justify in terms of commercial return if that return has to be realised uniquely from LTE 800 in Europe.

A longer term transition to spectral time sharing?

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

This raises the question as to whether there could be more broadly based reasons to promote half duplex FDD LTE as a mechanism for improving spectral efficiency in all LTE bands.

It could be argued that spectral efficiency is presently becoming progressively degraded.

This is the unintended consequence of heavy handed 'light touch' regulation.

For example the proliferation of multiple band plans has had a significant impact on handset sensitivity and selectivity

The proliferation of air interface standards has had a significant impact on handset sensitivity and selectivity

The problematic implementation of LTE and GSM in the 900 and 1800 MHz band with the implicit need for frequency guard bands will destroy spectral efficiency gains potentially realisable from LTE implementation.

The imposition of market efficiency theory dictating five bidding entities to maximise spectral auction income has resulted in compromised band plans.

These compromised band plans make it difficult to implement wider LTE channel spacing (10, 15, 20 MHz) needed to support variable data rates with high peak rates. An example would be a multi operator environment where a 35 MHz duplex has to be divided between five bidding entities

Time sharing is a possible solution and builds on already long established principles of pooled resources in the industry for example the tradition of mast sharing in the industry and more recent moves towards network sharing.

There was some discussion on the late 1990,s[53] that operators could bid for code bandwidth rather than frequency bandwidth. At the time it was felt that such a procedure would be insufficiently tangible for the investment community.

Multi operator time sharing of LTE channels is however a plausible alternative. Operators would have a right of access to time domain rather than frequency domain bandwidth.

Time sharing is already established in present cellular systems on a user to user basis for example the GSM 8 slot frame supporting 8 users in a 200 KHz channel

The decision was taken that UMTS would use code channels but HSDPA and HSDPA+ has reintroduced time sharing principles in HSDPA based on a 15 slot frame and 10, 5, 2 or .5 ms frame lengths

This could be extended so that multiple operators co share the same (wide band) LTE channel in the time domain

Timing and site coordination would be needed between operators to avoid differential round trip delays but this in turn could help with other co existence issues, for example DVB H, DVB T and LTE co existence.[54]

This would allow the theoretical benefits of half duplex FDD LTE (duplex gap flexibility, relaxed TX filtering and/or improved RX sensitivity) to be realised in practice and would suggest a more robust technical and commercial justification for half duplex FDD LTE.

6) Appendix 4

Summary of industry responses.

As an introduction to this section we would say that we would expect the responses documented in Appendix 4 to be more negative about half duplex than responses that operators are likely to receive from vendors.

This anomaly is easily explained.

[53] Based on discussions with infrastructure vendors in 1998

[54] Anecdotally there is an increasing interest in deploying DVB T rather than DVB H receivers in LTE handsets. This may suggest a future shift of emphasis towards optimizing LTE 800/ DVB T rather than LTE800 DVB H coexistence. Discussion with Cellmetric, 26th June 2008

As a component vendor it is hard to say no directly to an operator, particularly a Tier 1 operator with tens and in some cases hundreds of millions of subscribers. It is much easier to express your doubts and reservations to a third party. But saying yes to an operator unfortunately does not guarantee that devices will be available particularly with a vendor community that by default has to remain focused on servicing mainstream applications.

So if an operator asks a component vendor the question ‘Are you willing to produce components for a European half duplex LTE 800 handset’ the answer would probably be yes. If the operator then asks ‘Are you capable of producing components for a European half duplex LTE800 handset when we want them at a price we can afford delivering an acceptable performance’ the answer would also probably be yes. Both answers represent the triumph of optimism over practical reality.

Industry Responses

i) 10th June 08 Business development Director CRFS

Am I correct that when you say 'half-duplex' you are referring to Tx and Rx on the same frequency? If so, why isn't TDD the obvious option? (so much effort has gone into the TDD version of 3G by Nokia, the Chinese, and people like Interdigital that this would seem to be a more viable 'go to market' proposition).

Introducing a third transmission scheme on top of the established FDD and TDD systems sounds very risky - apart from the RF considerations, the changes to the signaling software and overall system management (e.g. radio resource management functions) will require support from handset, infrastructure and test system vendors that might well render it uneconomic. Would implementing HSPA on a duplex system not end up being very TDD-like in any case?

Comment

Yes half duplex allows overlapping TX/RX though most of the band plans proposed are still duplex spaced with a duplex gap – the rationale for half duplex is to allow the duplex gap to move around from country to country and relax the TX filtering specification - the RX filter paths remain more or less the same

TDD is beneficial for systems that rely on MIMO to achieve headline data rates. MIMO does not work as efficiently in duplex spaced bands.

At a system level TDD is limited to max 9.5 km cells due to the TX/TX time domain guard band needed

Operators at 700/800 MHz want the ability to implement large radius cells (35 km and above) which is easier and more capacity efficient with FDD

It is possible to put forward a persuasive technical argument for half duplex on the basis of band flexibility.

However half duplex incurs additional incremental work (and cost) and only benefits regulators and governments wishing to auction non harmonized spectral bands. Our contention in this study is that there is insufficient margin in the RF component business to fund this additional work. Additionally and crucially the people that need to invest (the RF component vendor community) do not directly benefit from the outcome of the investment. They are being asked to solve some one else’s problem with no related reward.

ii) Axiom Micro Devices) 10/6/2008

Axiom Micro Devices specialize in highly integrated CMOS based power amplifiers.

‘We believe that CMOS will prevail for the PA functionality. In the long terms we believe CMOS will be on a par with GaAs for efficiency.. As soon as this is the case then the cost benefit and reliability benefit will sound the death knoll for GaAs.

Once CMOS PA is the preferred solution it opens the path for integrating the PA with other components. Initially this will be transceiver, but in the future baseband as well. Such integration will bring all the normal benefits for cost and reliability, size etc.

Now a half duplex system is much easier to integrate than a full duplex system for reasons of on chip noise / interference. So for example, we believe that integrating a PA with a GSM GPRS transceiver will be much easier than doing this for WCDMA. This may not be insurmountable, but it is a problem which will probably add cost and delay.

*So **for the ultimate integration story, we think a half duplex system has better potential**. For example a single chip Wimax baseband, transceiver and PA looks quite do able.*

Furthermore, duplexers are relatively big and bulky, so removing these is good.

However, all this theory goes to pot if the phone (or whatever it is) still needs to support conventional WCDMA.

If there is a market for LTE half-duplex markets that do not require conventional WCDMA as well, then there seems to me to be a reasonable reason for doing LTE half duplex. For example a "phone" doing GSM for voice and half duplex LTE for data would be a good target for aggressive integration (if the market is big enough).

Similarly for an LTE based data-phone where voice is done VOIP style.

If this market doesn't exist, and all phones are required to support conventional WCDMA then I don't see any advantage in half duplex-ing the LTE portion.

Comment
This adds collateral to Nokia's position that there are no real benefits in term of cost if full duplex also needs to be supported in the handset.

It also confirms that a good technical case can be made for half duplex but only if universally employed.

iii) Nujira 11th June
Nujira specialize in broad band amplifier and broad band linearization techniques.

The following is the transcript of a call with Julian Hildersley 11th June 2008

'*Something needs to be done about the number of power amplifiers needed for next generation multi band handsets*

The solution has to be broader band amplifiers with associated broad band linearization techniques which will allow one power amplifier to cover a number of band plans or an extended operational bandwidth.

For example we have taken a digital TV RF PA capable of working across the whole UHF band (470 to 860 MHz) and have improved the efficiency of the device from 15% to 40%. The challenge is to replicate this performance in a handset. For example these techniques would be required in order to deliver an RF PA capable of supporting a common LTE 900 and LTE800 TX signal path with the longer term potential of accommodating LTE700.

Half duplex does potentially help with PA device integration (the same comment made by Alex above).

In terms of standards support, it is important to realize that China has invested substantial political capital in TD SCDMA and Chinese vendors including Huawei and ZTE have accrued substantial R and D experience in TDSCDMA handset and network design.

Much of this work could be repurposed into TDD LTE which in itself would make half duplex FDD more attractive from a system implementation perspective.

From a PA design perspective half duplex FDD is neither significantly more difficult nor significantly easier than TDD or full duplex FDD.

It comes down to addressable market size and the realizable added value achievable from device sales.'

Comment
Axiom and Nujira are two examples of early stage companies working in areas of innovation (on chip power amplifiers and broad band linearization) which are strategically important to the cellular industry.

It would however be imprudent to base spectral policy on future technology innovations particularly when implementation time scales and commercial viability remain unclear.

iv) Briefing with Avago 13th June 08

General comments

There is a general requirement from handset manufacturers to want smaller more highly specified (more linear) components. The premium for combining these two requirements (size and performance) is about 30%. Active devices, for example power amplifiers, have the additional issue of heat generation which may imply other cost multipliers.

PA comments

A common RF PA for LTE800/900 would be supportable given present advances in PA technology but would be problematic if LTE800 were half duplex and LTE900 was full duplex

Switch Comments

In a GSM/LTE phone the TDD switch is already in the phone and could probably be reused for half duplex Note the cost would be around 10 to 30 cents.

Half duplex user to user interference

User to user interference in half duplex is potentially a problem for indoor applications particularly if multiple devices are trying to communicate with a base station some distance from the house.(Devices will be at high power to overcome 10 to 15 dB of in building penetration loss and received signal will be low.

Note the present trend for users to own and use multiple devices, an office phone, a home phone and a data centric device. All three could self interfere.

The more devices there are that are physically proximate the more severe the interference.

Interference in indoor femtocells

A femtocell would reduce the power output of devices serviced by the femtocell but these devices would suffer interference from visiting devices still camped on to an external base station.

In HSDPA and LTE handsets this probably does not matter too much provided the victim devices can move to another channel in band or another band as and when a poor CQI (channel quality indicator) is reported.

Cross border handset to handset interference – half duplex and full duplex

Several of the band plans have overlapping TX and RX frequencies. Thus in border regions it would be quite possible for user 1 to be supported on country A's band plan and user 2 to be supported on country B's band plan.

Interference would occur irrespective of any filtering (this would be in band interference)

This is an argument in favour of cross border harmonization irrespective of whether full duplex or half duplex is implemented.

Symbol cover and effective bandwidth

Within a 5, 8, 10 or 20 MHz channel, the OFDM symbols can be arranged to occupy the centre of the channel and avoid the channel edge. This produces a reduction in the noise bandwidth which will realize a benefit in terms of receive sensitivity. There will however be a loss of resilience to interference.

v) Comments from Tier 1 PA vendor 7th July 08

1. *LTE was designed from the get go to learn from the mistakes and weakness of 3G. The quest for a so called "single" global standard that was commercially and technically structured for universality remains it's strongest feature and is why the other two horses in the race are a non-starter (UMB) or losing ground year-over-year (handset (not laptop) mobile WiMax/WiBRO). Vodafone, Verizon Wireless and China Mobile are all in the same LTE trials club.*
2. *Anything that dilutes the economies of scale that FD LTE brings is likely to be slow in uptake, if at all.*
3. *Battery life is a critical factor limiting ARPU in 3G but improving.*
4. *SC-FDMA was selected as the mobile uplink by 3GPP to allow the PA to run with better efficiency than competing OFDM(A) UMB and WiMAX PAs*
5. *What's more, the 23 dBm nominal power does indeed render a design target that aligns well with UMTS designs; as accurately cited in the report.*
6. *If indeed the argument for 3dB more power is correct then it disrupts 1-5 above. We and other PA Tier 1's will shy away from this.*

7. *Shannon-Hartley law basically says data rate is proportional to channel BW and S/N ratio.*
8. *Going to HD reduces Tx time that can be offset by increasing (scaling) channel BW if the you are already above the S/N ratio threshold to support a given modulation scheme.*
9. *So at a given distance from the base station, so long as the Tx power is sufficient to result in a S/N ratio that supports the chosen modulation then increasing power by 3dB will not improve data rate.*
10. *However increased power will extend the cell size and the S/N threshold will demand more power for say 64QAM (high data rate) than say QPSK (lower data rate).*
11. *If HD is adopted then we hope it will be the BW knob turned to offset duty cycle in time domain.*[55]
12. *From the duplexer standpoint going to an antenna switch and filter is accurately defined in the report. As Peregrine said, making a switch that simultaneously meets the UMTS (and FD LTE) linearity in terms of IMD under blocker conditions is complex when the same switch needs to have ports also optimized for harmonics, be that HD LTE or GSM. These so called WEDGE switches are now available an therefore the impact of HD LTE on the switch is nothing new other than more ports which drives total performance and cost. I may be right in thinking that any LTE handset will need backward compatibility with UMTS and GSM so those 2 standards already have the LTE FD and HD standards covered.*
13. *The Nokia comment that FD is going to leave duplexers in the BOM anyway is well taken.*
14. *HD does indeed reduce design constraint on RX band noise but as I read report the am I correctly seeing that HD and FD would be paired in the same phone anyway?*
15. *On the adaptive tuning topic I fully agree that the move to OTA test will drive its acceptance. That said I have to question whether one of the Charge Pump "needing" technologies (BST and MEMS) will make it to market if indeed a semiconductor technology can implement an integration friendly single chip tuner with low-enough loss and small size.*

vi) Comments Panasonic 11th July 08

The biggest issue with FD is the wideband noise floor from the PA (in a well designed TX!) due to the linear PA's noise figure. As an RF guy, I would much prefer to see a GSM-style half duplex with TX/RX frequency division, since this is the lowest cost approach.

If full duplex operation is insisted upon, then the higher costs will only be mitigated when economies of scale can drive the availability of duplexers (filter sets). This means that the operator community will have to all agree on one set - with as wide a spacing of TX and RX frequencies as the allocations will allow - or nothing will happen. Hardware supply wise, that is.

I'm not sure what the half duplex adaptive approaches you mention really mean. Is any clarification available?

The 3dB comment also baffles me. Tx power is TX power during any burst. SNR is set in real time, not by some longer term average. SAR is helped, because it is a long-term average. But demodulation is not - it operates symbol-by symbol. Unless there is something else going on, somebody is smoking something. Hopefully they will share....? ;-)

From a PA perspective, HD is much better because the self-jamming from the PA noise figure is essentially eliminated. Linearity wise there is no difference that I can think of.

I would vote enthusiastically for half duplex, given the opportunity!!

BTW - LTE will never have the same AM as QPSK from everything I have seen. Even though people call it a single-carrier modulation it is OFDM with an 11dB PAR.

vii) Additional responses

Responses were received from five RFIC developer/manufacturers on the impact of adding half duplex to a handset already supporting multiple FDD bands. The respondents requested anonymity due to the sensitivity of their development programs.

[55] In other words this PA vendor is saying keep the maximum power the same and maintain the uplink data rate by doubling the occupied bandwidth for individual users as and when required.

The possible range of impacts beyond simple performance might include delays in development due to the added complexity, poor prospects for return on the development expense, or, in the best and obviously optimistic case, no significant impact.

The structure of the handset semiconductor industry has changed significantly in the past year. Much of this activity was due to increased pressure on margins in the market segment, as well as the need for sufficient scale to justify the exponentially-growing cost of R&D in the cellular market. This consolidation will have an impact on suppliers' willingness to incur additional costs in developing variations of chips for niche markets where the return is not clear.

For example, **Agere Systems** was acquired by **LSI Logic**, which subsequently divested the wireless product line to **Infineon**. **NXP Semiconductor** acquired the **Silicon Laboratories** wireless product line, and subsequently has formed a joint venture with **ST Microelectronics** for handset semiconductors. **Analog Devices** divested its handset IC product line to **MediaTek**. **Intel** divested its baseband processor product line to **Marvell**. There has even been consolidation among startup companies, as evidenced by the acquisition of RFIC specialist **Sirific Wireless** by 3G baseband specialist **Icera**.

The feedback from the industry seems to indicate that the biggest issues, as identified earlier in this study, are related to the passive filter devices. In addition to the sheer number of different duplex filters required, at lower frequencies, the devices are larger and will as a result cost more, may take up more physical space, and will suffer some degradation in sharpness given that the fractional bandwidth is higher than the current WCDMA bands at much higher frequencies.

Indeed, initial prototypes of ceramic-resonator duplexers for the U.S. 700 MHz band have been delivered, and in the interest of keeping the physical size similar to duplexers used in higher-frequency bands, the attenuation of the transmit signal in the receive band has been poorer than needed.

In GSM radios, techniques have matured for integrating previously-external function blocks such as VCOs, loop filters, and even tank circuits. New radio topologies such as TI's DRP (Digital Radio Processing) have brought new signal-processing technologies to RF transceivers, enabling integration with the baseband and mixed-signal circuitry. Even radio transceivers based on traditional architectures have been successfully integrated with baseband and mixed-signal devices, as in the Infineon single-chip devices. Thus in GSM, the radio semiconductor cost is now quite low.

However, with the addition of many more bands and modes, including WCDMA, the cost of the filters and related switching ("everything between the PA and antenna") jumped to a much higher cost than the semiconductors. Over the past few years, as volumes for 3G handsets have grown, and development costs of the filters has been amortized, the costs are now reaching parity with the silicon.

However, adding more country- or operator-specific frequency bands will drive the cost of filters and related switches higher. This will be undesirable for handset manufacturers and consumers.

Radio IC developers were asked about the additional cost in the silicon to add a half-duplex option to a full-duplex radio. One engineer suggested that the transceiver under development for LTE at his company would comprehend the possibility of WiMAX operation using the same silicon, so provision is already in place for accommodating both full-duplex and TDD operation.

U.S.-based Bitwave Semiconductor has developed a family of radio transceivers designated "Softransceiver™" which use a software-programmable architecture. Their design allows a baseband processor to select the frequency bands for both receive and transmit between 700 MHz and 4.2 GHz, as well as varying the channel filter bandwidth from 25 kHz to 20 MHz. Bitwave believes that their radio will support the proposed full-duplex and half-duplex LTE allocations, provided that suitable RF filters are available.

Ironically, nearly every transceiver developer commented that half-duplex "makes everything easier and lower cost". Though not of course if full duplex also needs to be supported in the same handset. The silicon area (which drives the cost) is negligibly impacted.

Attention was turned to the baseband section of the terminal chipset to assess any impact of an additional mode. The response was similar to the transceiver developers: "If we have enough processing capability to do full-duplex, we can easily do half-duplex". The only possible caveat here is the possibility that a half-duplex option will require a doubling of the data rate to provide an apparent throughput to the user that is consistent with a full-duplex version. In this case, baseband processor developers may find their processing capabilities stretched, and new devices may be needed.

One baseband IC developer commented as follows:

> *"Covering this from just the baseband/sw perspective … I can't see any reason why this (supporting LTE in the 800 MHz band) isn't inherently supportable with the baseband. However I think it may be dangerous to assume that the fundamentals of HDD implementation can largely be inherited by virtue of being a subset of FDD and TDD. Although the premise is 'correct' according to the 3GPP specifications, I believe that TDD implementation in devices/platforms will largely be considered as lower priority than FDD and so their implementation/deployment in many of the mainstream platform/devices will either be delayed or not implemented at all (as was the case for WCDMA)....As a result, although likely to be inherently possible, we should not consider a shift to HDD to be a trivial step and would likely cause a timescale impact."*[56]

The connection between the radio and the baseband deserves some attention. Many manufacturers supply complete chipsets, with digital, analog, and radio all optimized with proprietary interfaces between them…sometimes analog, sometimes digital. However, there were some IC manufacturers that supply only the baseband and others that specialize in radio transceivers.

The DigRF group was established several years ago to define a set of standardized digital interfaces to allow transceivers from one manufacturer to be easily used with baseband processors from another. A standard interface was developed and published for GPRS. In April 2007, the DigRF Working Group was assimilated into the Mobile Industry Processor Interface ("MIPI") Alliance.

The MIPI organization membership includes the top 5 handset manufacturers (Nokia, Samsung, Motorola, LGE and SonyEricsson) and most of the major handset semiconductor suppliers (Texas Instruments, NXP, Freescale, ST Microelectronics, Infineon, Broadcom, Renesas, RF Micro Devices, Panasonic, Skyworks, and others).

The DigRF group published the interface between RF transceiver and baseband processor for EGPRS terminals in February 2004. It is worth noting, as mentioned previously that the handset IC industry has undergone significant changes since then; among the original working group member companies were Philips (now NXP), Motorola (now Freescale), Agere Systems (now part of Infineon), and TTPCom (now part of Motorola).

According to the MIPI web site at www.mipi.org :

> The group's current charter is split into short and long term development efforts. The short term development will focus on a specification targeted for completion by end of 2007 for LTE and WiMax air interface standards. The longer term development will focus on future air interface standards which promise further improvements in high speed, data optimized traffic. In addition, the future work will seek to harmonize efforts with the PHY and UniPro Working Groups.
>
> These specifications will describe the logical, electrical and timing characteristics of the digital RF-BB Interface with sufficient detail to allow physical implementation of the interface, and with sufficient rigor that implementations of the interface from different suppliers are fully compatible at the physical level.

It seems that the DigRF specification for LTE and WiMAX is slightly behind schedule. However, since the interface is being defined with sufficient bandwidth to accommodate full-duplex LTE, it is reasonable to assume that a half-duplex option will not present any difficulty unless the date rate is doubled to present the user with the same throughput in both full-duplex and half-duplex modes. If this is the intent, and a half-duplex option with double the instantaneous date rate is adopted, it is strongly suggested that the DigRF Working Group be informed as soon as possible.

[56] This agrees with other informal responses we have had commenting on the slow uptake on TDD versus full duplex FDD. In this context, half duplex FDD is seen as a sub set of TDD and as such represents incremental additional design work.

One respondent expressed concern about developing a dedicated transceiver or obtaining filters for a new band, specifically for one operator or country. The situation in Japan was cited as an example. With some specifications unique to that country's regulations, most global suppliers do not see sufficient scale to justify participation and consequently the supplier base is limited to mostly local Japanese suppliers. With little competition and insufficient scale, those suppliers have not lowered their costs quickly enough, and are not competitive in the world market.

RF MEMS – the future?
One of the problems in duplex (or any) RF filter development has been the inability to tune the filter. A tunable filter would simplify the front-end of a multiband transceiver by allowing a single component to replace a plurality of separate filters.

Sand9 is a startup company in Cambridge, Massachusetts engaged in the development of a promising new technology using MEMS for RF filters. Sand9 received USD100k of funding in November 2007 from the National Science Foundation. According to the award documentation:

> *The company has developed the world's highest-frequency mechanical resonator and will use this device to create programmable RF filters for wireless communications in the 100 MHz to 3 GHz ranges. The project will develop a 900MHz and 2GHz filter design, test and characterize the design, transfer the manufacturing process to a commercial CMOS fabrication, package the devices using standard commercially available methods, design and test a single pole double throw switch and integrate a switch and filter onto the same die. Each of these resonators can act as a high Q filter, and arrays of these resonators can be combined to create band pass filters of arbitrary bandwidth with low insertion loss and excellent outside-band attenuation. This potentially disruptive technology incorporates novel mechanical amplification of rigid nanostructures to achieve GHz resonant frequencies and RF performance levels not possible with MEMS scale devices. These filters will offer significant performance improvement over existing RF filter approaches with significant improvement in size, power consumption and filter performance. This platform will also allow additional devices such as clock oscillators and digital circuitry to be integrated onto the same chip. This technology will be used to replace existing discreet filters in cell phones and other mobile wireless devices with the ability to access many different air interfaces with excellent radio performance.*

While the company is not currently disclosing any further details of their progress, it is possible that by 2012 such technology, from this company or another, will be available to replace the ceramic resonator-based duplex filters of today in mass-produced high-volume wireless terminal applications. This could make country to country variations in band allocations easier to support technically and commercially.

7) Summary – the final answer?
Will half duplex help to meet the specific flexibility needs of the European band plan?

Yes in theory, it would allow the duplex gap to be implemented at different places in different countries.

*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 would suggest that the option will not be cost effective from an overall industry perspective. In terms of possible cost savings, the consensus view seems to be 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.

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.

Does the band plan (channel raster, duplex spacing and operational bandwidth) make any difference to the half duplex/full duplex decision?

Yes. If the design brief is to produce a handset that is capable of a 50 MHz TX band centred on or near 835 MHz and if the design brief is to support wider LTE channel bandwidths, for example 8 MHz and if the longer term aim is to have a common RF PA that can also cover the LTE 900 transmit band and in the longer term LTE 700 band.

This would mean that a broad band amplifier would be needed. As the operational band width increases (from 30 to 32 to 40 to 50 MHz or 100 MHz or more if LTE 900 and LTE 700 are included) it becomes progressively harder to manage the linearity in the PA. As the channel bandwidth increases, for example from 5 MHz to 8 MHz to 10 MHz to 20 MHz, the ACLR components produced by non linearity in the handset PA add to the handset RX noise floor.

Whether this is important or not depends on the duplex spacing (which determines the impact of internally generated interference) and the duplex gap (which determines the impact of ACLR on user to user interference).

Half duplex is one way in which this problem could be solved in terms of internally generated noise within the handset though generally the duplex spacing will be sufficient to ensure ACLR is not a dominant problem. The other way is to realise amplifiers that can be both linear and broadband.

The RX filter specifications will be similar for half duplex and full duplex and irrespective of the band plan.

Note that these design requirements are particular to the LTE 800 band (although LTE 700 also has some idiosyncratic performance requirements). For example no other band presently has TX operational bandwidths exceeding 4.3%.[57] 50 MHz at 830 MHz is over 6%. Add in LTE 900 and the TX bandwidth span increases to 130 MHz or over 15%. Several RF PA vendors have stated that 20% is achievable though not necessarily with 8 MHz or 10 or 20 MHz channel spacing and not without some compromise in TX efficiency in order to maintain sufficient linearity across the band. Half duplex theoretically makes the implementation of a broadband linear amplifier easier in that it mitigates the impact on handset RX sensitivity. However a half duplex PA will be characterised differently from a full duplex PA, for instance max power will be higher (3 dB or more). A PA for a half duplex handset is therefore perceived as an additional design challenge and as such will incur additional non recurring engineering cost. This of course assumes that the handset will also support full duplex.

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.

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.

This may suggest a need and opportunity to establish some form of industry led rather than academic collaborative device development programme though these initiatives are notoriously hard to realise.

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.

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[57] See Appendix 3 in the UHF cellular handset study for an analysis of operational bandwidths by band.

Does half duplex remove or lessen the need for spectral harmonisation in the LTE800 band plan?

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

LTE 850 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).

Superficially this does not seem technically or commercially attractive but may merit further study.

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 LTE 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.

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.

ENDS

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