RTT TECHNOLOGY TOPIC
October 2013

Multi Band, Multi Mode, Multi Carrier, Multi Stream, LTE user devices and the optimum value of N

This month's technology topic reviews how LTE is presently being deployed into new and existing spectrum, the related impact on user device performance, how this deployment will change in the future, the impact on future link budgets and how this affects LTE network economics and spectral value.

Contemporary smart phones typically support seven or eight bands, RFIC road maps are now suggesting 15 band support is likely with migration to twenty or more bands for LTE Advanced.

This is a description of the port support rather than a definitive indication of how many duplex filters will be populated in the RF front end of user devices. Given that each additional band incurs performance loss and additional cost then it is useful to question whether these high band count phones are going to deliver what operators need over the next three to five years particularly in cost sensitive low ARPU markets.

Most markets and many individual operators within specific markets have specific requirements that can generally be met with four or five bands supporting typically three technologies (GSM, HSPA and LTE for example). They also have specific requirements for carrier aggregation.

Curiously not a great amount of public domain information exists on the relative performance of low band count and high band count phones. There is even less information on the relative merits of different carrier aggregation options. Anecdotally it can be stated that user devices in the late 1990's generally worked better than conformance specifications often by a surprisingly large margin (6 or 7 dB). This is no longer generally the case particularly for high band count devices (for reasons explained below).

To take an extreme example, a 44 band phone covering all present 3GPP band options is analogous to having a family car with 44 seats with only one seat being used for most of the time.

So we thought we would explore whether it might be possible to establish an optimum number for N_1 (see table) defining the number of supported bands and their composite operational bandwidth, N_2 defining the number of supported carriers and their aggregated carrier bandwidth and N_3 defining the number of user specific simultaneous information streams.

	Operational bandwidth Band energy of interest			**Channel Bandwidth Channel energy of interest**			**User bandwidth User energy of interest**			**Application Bandwidth Application energy of interest**						
	MHz			MHz							mbps			kbps		
Low <1GHZ	30 by 30			3						Rate	100	10	1	100	10	1
	45 by 45			5							m			km		
Mid <2GHz	65 by 65			10						Distance	1	10	100	1	10	100
	75 by 75			15							m			sec		
High>2 GHz	70 by 70			20						Latency	1	10	100	1	10	>100
	90 by 90			100												
	Number of bands?		N_1=?	Number of carriers?		N_2=?	Number of information streams		N_3=	Simultaneous? → voice, text, data, image, video						
							Symbol recovery	Bit recovery								
							Resource block scheduling →									
Selectivity																
Sensitivity	→			→			→	→								
Selectivity																
		Saturation			Adjacent Channel Interference			Co Channel Interference								

More specifically we set out to test whether it is possible to resolve the following equation

$N_1+N_2+N_3$ = X (% increase/decrease in ARPU) = Y (% increase/decrease operator EBITDA)

An ability to resolve Y would provide a rational technically robust mechanism for valuing spectrum.

Five earlier topics provide relevant background

August 2012 the A to D in LTE
http://www.rttonline.com/tt/TT2012_008.pdf

September 2012 Acoustic Filters
http://www.rttonline.com/tt/TT2012_009.pdf

February 2013 Switches, Capacitors and Resonators
http://www.rttonline.com/tt/TT2013_002.pdf

March 2913 Carrier Aggregation Aggravation
http://www.rttonline.com/tt/TT2013_003.pdf

July 2013 OOBOOB Out of Band Out of Block Emission
http://www.rttonline.com/tt/TT2013_007.pdf

In the past, economic modelling of spectral value has been based on the assumption that all spectrum can be regarded as equal. Low band (sub 1 GHz) allocations provide coverage value, high band allocations (>2 GHz) provide capacity value and mid band combinations (1-2 GHz) provide a combination of the two. Ideally a well-balanced mobile broadband spectrum portfolio includes a combination of all three. This is reflected in present user device (smart phone) design with typically two or three FDD bands supported below 1 GHz, two or three FDD bands between 1 and 2 GHz and two or three bands above 2 GHz (Band 1 FDD, Band 7 FDD and TDD bands 38 or 40).

However this ignores the differences in user device performance determined in FDD by the operational bandwidth of the band, the duplex gap, guard band and out of block and out of band emission and in TDD by the operational bandwidth, guard band and channel to channel selectivity.

These differences are partially captured by user device conformance standards. Narrow guard bands and narrow duplex gaps and wider than normal operational bandwidths are accommodated by accepting lower maximum output power and reduced sensitivity. These relaxed specifications can then be used in link budget calculations and network economic modelling.

Compliance with conformance specifications is however tested in the conducted domain (with test equipment connected directly to the antenna output). This fails to capture the losses incurred from space constrained antennas in small form factor devices. These real life performance metrics are described as isotropic sensitivity (free space sensitivity) on the receive path and total radiated power on the transmit path and can be tested extensively though expensively in an anechoic chamber.

The result varies between different phones from different vendors but can be as much as 8dB worse than the conformance specification with the performance loss particularly evident in lower band (for example 700 MHz) and wider band (>4% operational bandwidth) allocations.

This means that the effective link budget for a phone working at 700 MHz with a wide operational bandwidth might be substantially lower than the propagation models would suggest. The performance loss can be mitigated by supporting narrower operational bandwidths in the lower bands and narrow band antennas in the user device front end. In the US 700 MHz band plan the 10 the 10 MHz bands used by Verizon (Band 13) and AT and T (Band 17) are examples of this.

This however makes it hard for other operators to deploy alternative band combinations particularly if they are technically difficult to deploy. Block A of Band 12 in the US is an example. The lower duplex (mobile transmit) is immediately adjacent to high power TV and therefore requires high reverse power isolation and TX filtering to prevent interference in to broadband TV receivers. The receive path is 1 MHz (0.14%) away from Channel 56 E block which together with Channel 55 will be used as a supplemental downlink channel or for LTE TV (eMBMS). Achieving sufficient receive path protection in a Band 12 Block A phone would result in unacceptably high insertion loss. To all intents and purposes Block A of Band 12 is a guard band, should never have been allocated for auction and should be regarded as having negative asset value.

It is also potentially problematic for the new APT (a) and (b) allocations in the 700 MHz band where a 45 MHz bandwidth requires two pairs of overlapping duplex filters. The combination of the additional switch path loss and inherently inefficient antennas and front end matching will make it hard to realise acceptable sensitivity from these devices which means that the potential range gains/data reach available from the band will not be achieved.

An alternative is to create a new band by extending the operational bandwidth of an existing band. The problem here is that the new band projects a performance loss on to the original band. For example the extension of the US PCS 1900 band (Band 2 with 5 MHZ added to the top of each duplex to create the new Band 25) reduces the duplex gap by 5 MHz and increases the operational bandwidth from 60 by 60 to 65 by 65 MHz. This softens the roll off of the duplex filter and reduces guard band protection at the lower band edge. The reduction in the duplex gap will result in a loss of sensitivity for **all** devices. Adding the MSS bands to Band 1 and extending the US 850 band will have the same effect.

So the benefits (capacity gain) of the band extension and the cost (performance loss) end up in different places. Performance loss (reduced sensitivity, selectivity and stability) in a user device has the direct effect of reducing capacity and coverage. This is a good starting point for pre or post auction litigation.

Anyway let us return to our table and consider the options for allocating and auctioning additional spectrum, for example in the 600 MHz band, in L band (between 900 MHz and 1.7 GHz) or C band (3.4 to 4.2 MHz) or above.

All these bands or rather groups of bands are candidates for incentive auctions where existing incumbents (TV at 600 MHz, military users at L band, satellite TV and microwave links at C band) are encouraged to make spectral assets available for auction to the highest bidder. Buyers and sellers in this process would benefit from an objective modelling methodology which captures all rather than some of the technology and

performance metrics that determine the realisable value from specific band and technology combinations. Arriving at a rational assessment of an optimum value of N for the number of bands, number of carriers and number of per user simultaneous information streams would be a good start.

Theoretically this could be relatively easily achieved by establishing whether increasing N improves or degrades the user experience.

The snag here is that there is no such thing as an average user or an average device or an average network. It might however be possible to establish a number of core user profiles based on application bandwidth (fourth column of the table). Present work on typical user profiles is already making this plausible. It then becomes valid to do higher order comparisons.

For example it can be demonstrated that increasing the number of bands and or their bandwidth increases front end losses in the user device. The user potentially has access to additional bandwidth though only if this is available at service provider level. Front end loss will result in a loss of sensitivity (downlink throughput), selectivity (uplink throughput and downlink interference resilience) and stability (over temperature over time). This increases power drain and reduces bandwidth efficiency.

Increasing the number of carriers and or their bandwidth will have a similar effect though at this stage it is A to D dynamic range and clock jitter noise which is the dominant constraint.

Increasing the number and or the bandwidth of simultaneous information streams will have a similar effect though here it is digital filtering and signalling which become the dominant overheads both in terms of power consumption and bandwidth efficiency.

Philosophically it is hard to avoid the conclusion that the mobile broadband industry is not short of bandwidth and indeed may now be at the point where adding bandwidth to user devices reduces rather than improves the user experience and increases rather than decreases network delivery cost. This is heretical and inconvenient for national regulators intent on realising consumer and industry value from a new wave of mobile broadband spectral investment.

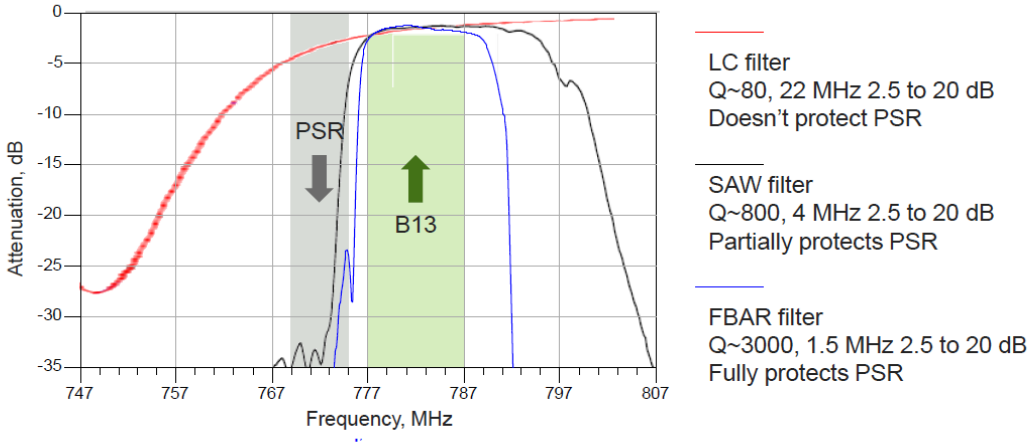
What we are short of is power. Battery capacity per litre per gram per CC is only improving at best at around 15% per year (and heat dissipation is improving even more slowly). The assumption is that network densification allows the RF power budget in a user device to stay relatively stable over time but this is probably a false assumption and certainly not valid for developing economies where sparse networks are required to achieve sufficiently low cost per bit to meet ARPU constraints.

Bandwidth Q as a proxy for power constraint

So if this thesis is correct what we need is a way to measure bandwidth quality rather than bandwidth quantity.

In an engineering environment the quality factor of filters and resonators is described using the term Q, a parameter that characterises the bandwidth of a resonator relative to its centre frequency.

The example (with thanks to Avago) compares three filters, an FBAR filter, a SAW filter and an LC filter and their relative effectiveness at protecting a potential victim channel, in this case public safety radio in Band 14 of the US 700 MHz band. The FBAR filter has a Q of 3000, the SAW filter has a Q of 800 and the LC filter has a Q of 80 with all three filters normalised to a 2.5 dB insertion loss. The LC filter would require a 22 MHz guard band to provide the required protection ratio, a SAW filter would require 4 MHz and the FBAR filter requires 1.5 MHz.



B13 Duplexer Tx filter and notch filter (steepest side) normalized to 2.5 dB IL

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This graphically illustrates the relationship between filter performance and bandwidth and insertion loss and characterises the performance cost imposed by the proximity of Band 14 to Band 13.

In practice the overall system cost is a composite of the insertion loss of the acoustic filter (the duplex filter in the RF front end), the insertion loss and noise floor of the LC filter ahead of the A to D, the truncation error and clock jitter noise of the A to D and the energy cost of the clock cycle count of the baseband digital filtering.

The dimensioning of all of these filter functions is determined by what the band is, where it is and what it is next to. Essentially bandwidth Q is a measure of the power cost of a specific band and channel allocation and will have a direct relationship with the end user experience including data reach and power consumption (user data duty cycle).

But surely this ignores the need to deliver ever increasing bandwidth?

At this point you might argue that this approach ignores the need to provision progressively more bandwidth to meet progressively more demanding user application requirements and of course more users.
Capacity calculations are based on the assumption that per user data rates will continue to increase but this of course assumes that the value of higher data rates is higher than the additional cost. A proxy for this assumption is the speed of trains over time. In 1829 Stephenson's Rocket achieved a speed of 29 miles an hour. 100 years later The Flying Scotsman could achieve 100 miles an hour. A century later we are debating the merits of spending £50 billion on a high speed train in the UK which will run at 250 miles per hour but it is questionable whether most of us would want to pay a premium price to save twenty minutes on a journey to Birmingham and none of us fly on Concorde any more.

And there must be some practical limitation to the amount of analogue bandwidth that we can practically consume. It might just be the case that data demand calculations based on progressively high per user headline data rates might be based on false assumptions.

High headline data rates are not intrinsically power efficient or cost efficient and pointlessly extravagant if server bandwidth is constrained. The important measurement metric is average throughput, energy per information bit and cost per information bit. Average throughput decreases and energy per bit and cost per information bit increases as user device performance decreases. TDD is not the answer. All that TDD does is translate the sensitivity, selectivity and stability issues of FDD from the frequency to the time domain. This is only an advantage if all networks are co sited and synchronised which is presently unlikely.

On this basis it is likely that operators will get a better return from making existing FDD and TDD bandwidth work better rather than adding new bandwidth which would now appear to be following the law of diminishing returns.

Summary

Additional bandwidth delivers a net economic gain provided the value of the user experience gain exceeds the additional cost of delivery.

The cost of delivery is a function of what the band is, where it is and what it is next to (the WWW of spectral economics).

This cost can be captured by establishing the value of N as an expression of the number of bands, the composite bandwidth of the bands and their relative requirements in terms of front end band pass filtering, N2 as an expression of the number of channels, the composite bandwidth of the channels and their relative requirements in terms of channel filtering and N3 as an expression of the clock cycle overhead and jitter induced noise and inter symbol interference of the digital filtering required to discriminate individual per user data streams.

This can then be used to establish or at least estimate X as an expression of the net gain in consumer experience value which in turn can be used to calculate Y which is the increase in EBITDA which in turn allows spectral assets to be valued.

While the absolute value might be open to debate the relative value should be accurate and provide a useful and valid mechanism for qualifying bid and auction strategies.

It is however possible that new spectrum may not deliver a gain in user experience quality or may result in a loss of quality or project a loss of quality on to other users of spectrally or geographically proximate spectrum. In this case the spectrum would have negative asset value.

Bandwidth Q, a composite of the filter overheads associated with a specific band allocation and channel structure provides a mechanism for establishing the net asset value including the threshold point at which that value becomes a negative number. This will be influenced by different combinations of N_1, N_2 and N_3. Higher values of N1, N2 and N3 will increase the need for Bandwidth Q. This may result in a decrease rather than increase in user experience value (X) and lower EBITDA (Y).

Simply put, improving existing spectrum for example by improving user device RF performance will probably yield a better return than buying new spectrum. It is the quality of spectrum (the RF link budget and related RF power requirement) rather than the quantity of spectrum which determines the user experience.

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