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Spectral and Spatial Efficiency

With just a few weeks to go before the next World Radio Congress, this month's technology topic reviews the factors that determine spectral value and considers alternative spatial efficiency options for delivering cost economic fixed and mobile connectivity.

The financial return achievable from mobile broadband spectral and infrastructure assets is traditionally modelled on a calculated spectral efficiency defined as the net data rate in bits per second (bps) divided by the bandwidth in Hertz.

This is a valid basis for comparing the relative standalone throughput efficiency of a particular technology but does not factor in the potential negative impact on other users within the same band or in adjacent proximate spectrum.

There is also a tradeoff between spectral efficiency, bandwidth efficiency and power efficiency.

The most spectrally efficient technology choice is not necessarily the most economically efficient technology choice.

Spectral Efficiency over Time

100 years ago spark gap transmitters began to be replaced by tuned circuits to realise more spectrally efficient and power efficient long distance communication initially at long wave, medium wave and short wave.

Improvements in filtering, power amplification and signal detection provided the basis for achieving a combination of increased range and higher throughput both for broadcast and two way wireless communication.

From the 1930's onwards FM modulation delivered a significant gain in voice and audio quality and increased frequency stability enabled a transition to VHF.

System efficiency gains were also achieved by implementing analogue compression in the frequency domain (pre-emphasis) and amplitude domain (companding). These techniques also helped to facilitate narrower channel spacing in two way radio systems, the implementation of 12.5 KHz channels for example.

These narrow communication channels deployed within narrow pass bands produced well filtered low noise long range radio systems.

They also provided the basis for cellular frequency re use. The principles of cellular radio were understood and patented in 1948 by the Bell Laboratories but only became practical in the late 1970's with the advent of low cost micro controllers and low cost high quality FR4 printed circuit board material to support operation in the 800 and 900 MHz bands.

1948 was also the year in which Claude Shannon and Ralph Hartley and Robert Fano published their work on the Mathematical Theory of Communication in the Bell System Technical Journal with Shannon's paper establishing the throughput limits of a channel with noise and the theoretical limits of digital compression.

The advent of digital voice codecs in digital cellular systems in the early 1990's and the parallel implementation of video and audio codecs in TV broadcasting took radio systems significantly closer to the Shannon limit and allowed for significant spectral efficiency improvements which in turn enabled parts of the radio spectrum to be repurposed, the migration of TV to the lower end of the UHF band and its replacement with cellular systems being a notable example.

Compression efficiency continues to increase, for example to support 4K and 8K TV transmission but the cost of incremental improvement increases over time. High efficiency codecs for example exhibit error extension if exposed to high burst error rates so link budgets need to be increased and interference needs to be managed more proactively. All things being equal, halving the error rate will require an extra 3dB of link budget.

Broadcast TV and other fixed wireless radio systems including point to point radio have relatively predictable channels that can be accurately characterized to support optimum channel coding and modulation. This is not the case for mobile broadband which means that in practice it is harder to deliver high spectral efficiency at system level.

But hard does not mean impossible and infrastructure vendors have heralded each successive generation of cellular technology as being more spectrally efficient than its predecessor.

These claims need to be interpreted with a measure of care.

3G was promoted as a replacement for 2G on the basis of its ability to support a step function increase in data throughput partly through allocating new radio bands but also by improving the spectral efficiency of each band.

The spectral efficiency gain was realised by a combination of higher order modulation and improved channel coding coupled to baseband spreading gain.

However higher order modulation degraded the efficiency of handset and base station amplifiers and out of band emissions increased. Out of band emissions could be reduced by additional filtering but this introduced additional insertion loss and pass band ripple.

The spreading/de-spreading process also required symbols to be received at the base station at equivalent power level which could only be achieved by supporting a bandwidth hungry and power hungry control loop.

At coding level, integrated adaptive modulation and coding schemes reduced residual bit error rates but the convolutional coding introduced additional baseband processing which consumed power and introduced a fixed delay. Block coding added more processing overhead and delay variability (jitter).

In parallel, handset designers were tasked with shoe horning multiple technologies and additional radio bands into space constrained and power constrained devices. This resulted in a loss of RF efficiency in the handset.

This generation of handset still passed conformance tests but performed poorly when tested in an anechoic chamber. It was not uncommon to come across handsets with a front end loss of the order of 8 to 10 dBm over and above the conformance specification. This loss translated directly into a loss of link budget which translated directly into a capacity loss, reduced coverage and significantly lower spectral efficiency.

4G mitigated these device issues by introducing techniques such as antenna aperture tuning that at least partially recovered some of the performance loss. Improvements were also made in switch path multiplexers and high count duplex filter efficiency.

At network level, the LTE physical layer is significantly better behaved than its 3G predecessor although its geographic reach is still poor and it is still power inefficient. The addition of OFDM delivers improved performance in fading channels but is inherently power hungry and can produce OOB emissions that are problematic to other networks and users in the same band or adjacent bands including Wi-Fi or ISM networks in adjacent unlicensed spectrum.

5G moves the spectral efficiency narrative forward by implementing beam forming on a per user per device basis

The theoretical gains from beam forming are significant, of the order of 40dBi to 50 dBi. This can be translated into coverage and capacity gain with the capacity gain being effectively a proxy for spectral efficiency.

RF power efficiency is also theoretically improved. If everything works, a higher percentage of wanted energy is transmitted where it's needed and a higher percentage of unwanted energy is nulled out in the receiver antenna array.

However in practice active beam forming in lower frequency bands is inefficient and ineffective due to insufficient element separation in user devices. Size, cost and wind loading constraints on towers and rural and urban cell sites add cost and complexity to the infrastructure offer.

Size and wind loading become less of a problem at higher frequencies, for example Ku and Ka band, but there are still significant processing overheads that will offset the potential realisable isotropic gain.

For example, an adaptive antenna array needs to compute angles of arrival and departure for wanted and unwanted signal energy.

This requires real time characterisation of the channel. This is easier to achieve if the receive and transmit frequencies are the same, in other words a time division duplex physical layer. However implementing a high bit rate wide area TDD network is significantly more challenging than an FDD network particularly if spectrum is shared between operators with differential inter-site path lengths. There will also be coexistence issues if TDD and FDD networks are deployed in the same or adjacent spectrum.

At device level, a TDD receive switch path will have significantly lower sensitivity than a well implemented FDD switch path and will be inherently noisier on the transmit path.

Additionally some of the device challenges that bugged 3G handset designers begin to reappear, particularly how to deliver effective and efficient beam forming in a small form factor device.

Thus while it is relatively easy to see how beam forming can realise gains in channels where propagation conditions change slowly or by small amounts it is hard to see how real gains will be realised in high mobility networks particularly for hand held devices.

Adaptive beam forming does work in some highly dynamic environments and can be implemented at comparatively low cost at high frequencies, automotive radar at 77 GHz being a particular example,

But a hand held device or small IOT device is smaller than a car and has to work off a sub 3 volt power supply and capacity limited battery.

There is however a solution.

The challenge with 5G is that it requires additional network density and additional network and device complexity to deliver performance gain.

The performance gain has to be a combination of spectral efficiency gain and power efficiency gain.

Spectral efficiency remains an important aspect of mobile broadband network economics though arguably less important over time if upwards of 30 GHz becomes available for co sharing. It is for example inconceivable that the per MHz price levels achieved by the 3G and 4G auction process will scale on a linear basis to Ku and Ka band.

By contrast, power efficiency both at user level and network level is becoming more important over time. Active beam scanning in a handset will be irrepressibly power hungry and battery drain will dwarf any benefits from the achievable isotropic gain.

The answer is to move the complexity somewhere else and the power somewhere else. In previous technology topics we have suggested that the best ‘somewhere else option’ is the ‘up in space option’.

The reason for this is that a power efficient handset needs to know where to look for a signal. A high count LEO constellation coupled to a MEO and GSO service offer will be nearly always nearly overhead.

An embedded passive but highly directional multi element antenna array in a smart phone screen can therefore be pointed directly upwards at the sky without any processing overhead and by default be seeing the strongest receivable signal.

The space infrastructure potentially includes massive antennas with hundreds of dB’s of isotropic gain achieved from high count arrays (1024 element and higher) handling hundreds of kilowatts of solar generated power or a highly distributed equivalent (thousands of cube sats for example). Given the absence of wind loading and space constraints, these space based arrays could scale down to UHF to include existing 5G sub one GHz spectrum including Band 71 (the 600 MHz band).

The International Space Station is of course the best known near earth large scale man made object but was painstakingly constructed by astronauts with space spanners – the stone age of space construction.

The alternative is to have structures that remotely self-assemble themselves in space.

Airbus for example have been investigating the business case and technical practicality of a self-assembled Vast Satcom (VASANT) antenna configured as two compound phased array fed reflectors 32 metres across each supporting 16 beams. Throughput is calculated at 140 Tbps equivalent to 100 times more than existing high throughput (HTS) satellites. This would be sufficient to support up to 70 million regional (continent scale) users in mobile broadband applications including cars, trucks, trains and boats and planes coupled to an ultra-fast home broadband service offer.

Deployed as a geostationary geosynchronous platform, the economics do not presently scale to direct connectivity for low cost hand held user devices but could be combined with high count LEO and MEO constellations as part of the delivery mix. As always, the constraint for geostationary satellites will be signal blocking at higher latitudes.

High count LEOS are the ultimate answer to this signal blocking issue with the additional benefit that signals sent and received from directly overhead can co share spectrum with terrestrial networks in the same band providing connectivity at lower elevation angles, for example from terrestrial towers and roof and street level base stations.

A dual use model that supported satellite connectivity for all 5G users in present sub 3 GHz spectrum would effectively double 5G spectral efficiency but more importantly provide truly geographic coverage.

The ability to scale these lower orbit platforms in terms of their size and power and signal gain capability, adding capacity as and when required, would mark a further significant step in realising ubiquitous low cost fixed and mobile broadband satellite connectivity. Spatial reuse delivered from space is an important part of this story.

5G and Satellite Spectrum, Standards and Scale

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00 44 7710 020 040