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Beam Economics

In this month's posting, we look at the efficiency, effectiveness and economics of modern day 5G and satellite adaptive electronically steerable arrays (AESA antennas), the direct descendants of the short wave beam radio systems deployed in the 1920's.
https://www.rttonline.com/tt/TT2018_004.pdf

In particular we look at the close relationship between antenna array efficiency and the economics of present and next generation cellular and satellite networks.

Present 5G networks at C band (3.5/3.7 GHz) are generally implemented as 65 degree sectors subdivided into eight micro sectors. The beams for each micro sector are managed using beam specific synchronisation signals which are unique to the 5G New Radio standard and as such provide a promising basis for improving the 5G value offer. A useful amount of gain is achieved which can be traded as additional capacity and or coverage, for example allowing C band 5G networks to co share sub 3GHz base station sites.

In the longer term, the need to provide broadband access to slow and fast moving users and/or IOT devices implies a need to support narrower beam width steerable antenna arrays in the FR2 bands above 6 GHz. This presents a number of implementation challenges for RF hardware and can lead to a gap between theoretical and actual performance often described as implementation loss.

This is not always obvious in early deployments where a limited number of users contribute to a relatively low noise floor. As networks become loaded, any shortfall in RF performance will have an impact on capacity and throughput.

Read on

At its simplest, a directional antenna can be constructed by adding a reflector to a collinear omni-directional antenna, or by adding more elements and a reflector to a Yagi antenna, a roof top terrestrial TV antenna being one example.

A more complex beam pattern can be achieved by physically moving two or more coupled antennas closer or further apart. The physics of creating beam patterns by changing the physical distance and/or phase difference between multiple antenna elements and the amplitude of the signals applied to them is therefore well established and remains the underlying mechanism used to achieve directional gain and or interference mitigation.

The parallel universe of military radar has also yielded a deep understanding of the science of calculating the angle of arrival of RF energy. In a reciprocal radio channel, this equates directly to the required angle of departure. The algorithms used in the adaptive antenna arrays in present and future satellite radio and 5G systems are therefore analogous to the maths used in radar based anti-missile missile systems over the past fifty years.

However maths is the easy bit. The big challenge with AESA antennas for 5G is to deliver efficient linear power at a cost at least two orders of magnitude lower than equivalent military hardware but with equivalent levels of through life hardware reliability.

The same constraints apply to flat panel steerable antennas for ground based satellite transceivers where cost targets of $1000 dollars are regarded as ambitious. In practice $100 dollars would be closer to the mark for mass market consumer applications with 10 dollars being a long term aiming point. This is challenging given that each element will usually have its own RF power amplifier and RX/TX chain.

Much work has been done on 5G channel modelling and satellite channel modelling all of which is valid and useful.

However history tells us that every new generation of cellular radio has been introduced on the basis of link budget assumptions that have initially proved to be optimistic. The reason for this is that implementation loss has not been fully factored into the network performance and cost calculation. Satellite business models can be based on similar erroneous assumptions.

Implementation loss is the gap between the theoretical RF performance of user and IOT devices and actual performance and the gap between the theoretical RF performance of the base station and its actual performance.

Network calculations are based on various assumptions including path loss and the overall link budget which takes into account transmit power and receive sensitivity and theoretical antenna gain.

Path loss includes factors such as rain fade margin which becomes particularly important at higher (millimetric) frequencies for larger terrestrial cells and/or for lower elevation satellite links travelling through substantial cloud cover.

For example the path loss for a 200 metre radius cell site at 28 GHz can be assumed to be of the order of 135 dB. This dictates the required transmit power and receive sensitivity. The economics of the network are predicated on achieving a 27dB gain from a 256 element array on the down link and 21dB of gain from a 64 element array on the uplink.

While these assumptions may be a fair reflection of antenna array performance when modelled in isolation, they do not take into account losses in the feed networks and for hand held devices, capacitance effects and related noise and power matching impairments over the required operational bandwidth.

The starting point here is to consider how phase off sets should be managed between individual elements and the rate of change needed if beams have to follow individual users.

Most present implementations assume a hybrid mix of analogue and digital beam forming. One option is to use analogue beam forming to shape a number of beam patterns and digital beam forming to shape user specific beams.

In digital beam forming, the phase off set is a function of time delay referenced against the digital clock pulse. In analogue beam forming, additional delay lines can be switched in using either MMICS or MEMS devices or by using a continuously tuneable dialectic such as barium strontium titanate (BST) or liquid crystal.

The efficiency of these electronically tuneable phase shifters is measured as the ratio of the maximum differential phase shift and the highest insertion loss in all tuning states bearing in mind that any phase shift function must have a flat phase response over the frequency bandwidth. BST has some advantages up to 10 GHz and liquid crystal produces some theoretical performance gain above 10 GHz due to low dielectric loss.

However a theoretical performance gain has to be tempered by operational requirements which for a satellite flat panel array include looking directly at the sun. A typically specified temperature range would be -40 to +65 degrees Celsius which can be easily exceeded.

As a consequence, any flat surface being used outdoors needs to accommodate a temperature gradient from below freezing to hot (125 degrees Celsius) so any phase shift process and related frequency and amplitude stability functions have to be more or less temperature neutral.

The same applies to low noise amplifiers on the receive path and power amplifiers in the transmit path, given that any increase in temperature translates directly into a higher noise floor.

This brings us back to the question of cost and heat rise over wide temperature ranges.
A classically realised adaptive electronically steerable antenna array has dedicated low noise amplifiers and power amplifiers for each antenna element. Hybrid digital analogue beam forming systems will also have multiple power amplifiers but shared across a number of sub arrays.

The efficiency of the transmit path, particularly if extreme temperatures have to be accommodated at Ka-band can be of the order of a few per cent. This can be mitigated by the use of gallium nitride or equivalent added value material processes but this cannot be generally accommodated in low cost arrays targeted at consumer applications.

Antennas for the FR2 bands, particularly arrays with high element counts will also suffer from unwanted element interaction either due to spatial proximity, aperture coupling and or surface wave interaction. Individually or together this will change the input impedance of the elements which in turn will dictate the gain, scan and polarization performance of the array. A percentage of the radiated power from each element acting as a transmit path will be distributed between the other elements on the array behaving as receive antennas. TDD theoretically mitigates these effects though can be compromised by inter symbol interference. Unwanted phase addition of a radiated field in more than one direction will generate grating lobes which in severe cases can reach the level of the main beam in some directions.

The answer may be found in the satellite sector though caveats apply.

The satellite industry, particularly the new LEO players such as OneWeb, Star Link and Project Kuiper need to solve the cost/performance issue of flat panel antenna arrays. Specifically this is evidenced by the need to compete with terrestrial 5G networks or provide cost effective complementary coverage.

In previous technology topic postings we have highlighted the inherent advantages of co-operation between terrestrial and satellite systems in the 5G delivery offer.

This includes dramatic reductions in space delivery cost. This is a function of rocket size, reliability and reusability. The present launch cost on a Falcon 9 rocket to low earth orbit is of the order of $3000 dollars per kilogram but this reduces to $1500 dollars per kilogram for a Falcon Heavy launch indicating the present rate of rate reduction.

The economic and added value benefits of delivering connectivity from space are well rehearsed and include free electricity, no rental costs and global coverage combined with extended life expectation (twenty rather than seven years in orbit for next generation electric satellites).

However these economic gains have to be balanced against the additional path loss that needs to be accommodated to get to and from space. For example, a 600 kilometre Ka-band link has a path loss of the order of 180 dB; a Ku-band link to a geostationary satellite has a path loss of the order of 210dB. These make the equivalent 135dB path loss in a 200 metre terrestrial cell site look relatively trivial.

Additionally there is an assumed need for a flat panel array to scan to low elevation angles to allow connectivity with a LEO moving from horizon to horizon and or to provide in building coverage through windows. The orbit height dictates the orbit time, typically about 120minutes, this in turn dictates the horizon to horizon time which in turn determines the track rate of the beam which in turn dictates the performance needed from the phase shifters.

The snag here is that antenna efficiency in a flat panel array falls at lower elevation angles. As the scan angle increases there will be less TX power on the main lobe (lower gain) and the beam will broaden which will increase interference on the receive path. The impedance of each element will also change as the scan angle changes.

The link will have a longer path through the atmosphere which means that the fade margin needs to be increased. The rain fade margin for rain at one inch per hour at 28 GHz is 7 dB per kilometre. This equates to a manageable 1.4 dB over a distance of 200 meters compared to potentially several kilometres of rain attenuation for a low elevation link to a LEO near the horizon.

Nothing much can be done about rain fade (apart from finding an alternative link) so the main focus has to be about improving overall antenna efficiency. Kymeta and Alcan are working to find innovative solutions that are claimed to deliver improved performance at a viable price point.

Alcan, an acronym fo**r** **A**daptive **L**iquid **C**rystal **An**tenna are basing their approach on low dielectric loss liquid crystal based phase shifting. Kymeta are working with the LCD division of Sharp to realize a diffractive Meta surface that allows an antenna beam to be defined holographically, an approach that has the significant cost advantage of needing only one PA for the whole array rather than a PA for individual element or element groups. Note that this is not just a component cost advantage. In a traditional AESA, the gain and noise characteristics of each amplifier need to be individually characterised. This can take more than a day of test time and that is before the array is put into an anechoic chamber for a system level test. Kymeta also claim high efficiency at low elevation angles.

However it is fair to say that irrespective of the technology used it is unlikely that a space facing AESA antenna will ever deliver significant gain over and above a 5G smart antenna where the beam forming only needs to be achieved across a relatively narrow range of elevation and azimuth angle. 5G antennas are also not looking directly at the midday sun so are exposed to a less extreme operational temperature range.

Part of the problem disappears as and when the number of new LEO satellites is sufficient to realize a link that is nearly always nearly overhead. At this point an inherently expensive power hungry temperature sensitive active scanning antenna can be replaced with a low cost power efficient passive fixed beam antenna with a narrow cone of visibility looking directly upwards. This has the advantage of delivering cost efficient temperature tolerant gain and high levels of interference rejection.

Additionally, assuming that launch costs continue to reduce at their present rate it becomes progressively more economic to put more power and more gain and selectivity and sensitivity into space.

But to put this into perspective, a 20 degree cone of visibility from a passive flat panel array implies 20,000 satellites to be placed in low earth orbit to provide continuous coverage.*

This illustrates the need for business models to be based on real life rather than theoretical performance with a particular focus on the assumptions made about antenna efficiency in size constrained hand held user and or IOT devices and or in applications that need to accommodate extreme temperature variation, for example a sky facing conformal antenna in a car or truck or base station antennas exposed to extreme weather conditions.

Additionally cost models need to include pesky but important details such as test time and test methodology, the power needed to get to and from space based communication systems and non-line of slight loss and surface absorption and scatter in terrestrial systems.

The assumption is all too easily made that digital radio sub systems are inherently amenable to performance optimisation. In reality these are RF devices that can easily suffer from unwanted coupling between elements. This will result in distorted radiation patterns, scanning blind spots, port impedance mis-match and feed resonances compounded by amplitude and phase errors that further compromise beam pattern and efficiency. RF hardware inconveniently does not follow Moore's law so any increase in complexity translates directly into added cost. Any individual antenna element failures through life will distort far field beam patterns, compromise side lobe nulling and negatively impact scan performance and effective steering range.

These caveats aside, beam forming is undoubtedly the shape of things to come with beam economics as yet another new buzz word in the world of network economic modelling. Beam shaping, beam switching and beam tracking promise to be equally beneficial to terrestrial and or space based systems but may not live up to initial expectations.

*Our thanks to New Street Research for this insightful calculation
https://www.newstreetresearch.com/

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