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Noisy Networks

This is the third and final technology topic/posting on the RF Economics of the Millimetre Band.

In the October Topic, Millimetre Metrology, we reviewed beam forming and beam steering and associated test cost and performance uncertainty. New Radio and New Space in November looked at the cost and performance issues of millimetre band user devices and consumer premises equipment

This month we look at link budgets for terrestrial 5G in the millimetre band (5G FR2), the comparative economics of Ku and Ka band satellite networks and the cost implications of RF component performance constraints.

For understandable reasons much of the present focus of 5G terrestrial implementation is on upper S band and C band deployment between 3 GHz and 4 GHz. This is partly due to technical convenience, products and networks are easier to build and the density economics are presently better than higher frequency options and partly due to regulation with satellite operators incentivised to make space for 5G by upgrading C band GSO satellites to work in 200 MHz rather than 500 MHz of C band spectrum.

This has been good news for the satellite manufacturing supply chain and has opened up opportunities for delivering converged terrestrial and satellite C band services including 5G and broadcast TV and in band backhaul provided TDD (terrestrial) and FDD (space) coexistence and competition issues can be resolved.

The question is whether and or when this model could and should be extended to Ku band at 12 GHz, a satellite TV band also used for rural broadband connectivity (Starlink as a present example), Ka band at 28 GHz and the millimetre bands above 30 GHz where channel bandwidths of up to 1 GHz within 3.5 GHz pass bands become technically feasible.

There is significant baseband vendor enthusiasm for the millimetre band. Network density and wide channel bandwidths at higher frequencies increase the need for clock cycles but this enthusiasm is tempered by link budget limitations and an understanding of the differences between ‘low band’ (sub 7 GHz) and ‘high band’ (Ku band and millimetre band) radio networks.

As a rule of thumb it can be stated that lower frequency networks are capacity limited and higher frequency networks are power limited.

Regulation has made capacity cost a particular issue for ‘low band’ terrestrial cellular networks. A limited amount of spectrum has been auctioned at high prices to multiple operators who share spectrum in a way that reduces spectral efficiency (the cost of guard bands and OOB emission constraints). Capacity gain is realized though network densification with an associated capex and opex cost.

Radio air interfaces and radio hardware have therefore been optimised to improve spectral efficiency by mandating higher order modulation and for 4G and 5G by the use of **beam forming**. Components and systems have evolved to help deliver spectral efficiency and minimise associated power efficiency cost, for example by implementing transmitter linearization techniques. Beam forming is more easily optimised in TDD networks as channel sounding is reciprocal though time domain interference can be an issue.

Interference (in the frequency and time domain) is normally assumed as the dominant constraint to capacity. Interference in turn determines minimum inter-site distance.

Inter site distance also sets the boundary for minimum coupling loss specified for 5G as 45 dBm for Pico Cells at 2 metres, 53 dBm for Micro Cells at 5 metres and 70 dBm at 35 metres for Macro Cells. The coupling loss is line of sight and does not account for other propagation losses.

Coupling loss is also used as a term in satellite network planning but is more accurately described as spreading loss and describes the decrease in flux density due to distance and inclination.

Self-evidently the minimum coupling loss of a satellite network with a distance between receiver and transmitter of several hundred kilometres is going to be several orders of magnitude higher than a 5G terrestrial network. This might seem like a problem but isn't as it is the link budget rather than coupling loss or spreading loss which needs to be considered. The link budget to and from space can be surprisingly close to, and sometimes better than a terrestrial network deployed in Ku band and above.

Partly this is due to non-line of sight loss which increases with frequency. Surface absorption rather than reflection becomes dominant adding capex and opex cost to high frequency terrestrial networks where line of sight can be hard to achieve.

Satellite networks have the similar but different problem of reduced flux density at low elevation angles and blocking from buildings and foliage but this is mitigated once you have enough satellites (20,000 or so) to deliver nearly always nearly overhead connectivity. High inclination also minimises spreading loss.

Terrestrial and satellite networks deployed at higher frequencies have relatively large amounts of spectrum. For the satellite industry this has meant that radio interfaces and radio hardware have generally been optimised for power efficiency rather than spectral efficiency, for example by using constant envelope ASK modulation and more highly specified RF components.

This brings us to the topic of noisy networks, starting with the gain budget.

In existing cellular networks, for example at 800 or 900 MHz, the maximum power you are ever going to see in a hand held user device is of the order of **33 dBm/2 watts** with most devices designed to work at a maximum of **23 dBm (200 milliwatts).** The maximum power at a base station will be of the order of **43 dBm (20 watts).**

While it is feasible to have 20 watts (43 dBm) in consumer premises equipment for a space uplink it would be expensive at higher frequency. It therefore makes sense to put more downlink power and higher uplink sensitivity into space but there is a launch cost penalty and issues of uplink interference and front end dynamic range.

The International Space Station (400,000 kg) has two thousand square metres of solar panels generating 120 kilowatts of power. The latest Iridium Next satellites (800 kg) have 2 kilowatts of on board power which supports power allocation of 50 watts for hosted payloads at a 100 kbps average data rate but this is a narrow band L band network with 10 MHz pass bands. On board power is also needed for the Ka band cross links and to maintain other functions on the satellites.

A GSO satellite (6000 kg) might typically have 15 kilowatts of power available; enough to deliver several kilowatts of power to a satellite TV down link but these platforms are not designed to support a power constrained duplex or half duplex uplink.

4G and 5G base stations in space with 900 square metres of solar panel arrays are also proposed. This implies potentially kilowatts of power but this then makes it hard to realise sufficient uplink sensitivity, even when working half duplex at S band. Clocking coexistence with TDD terrestrial C band would also need to be resolved.

The millimetre band will have higher propagation losses and will need significantly higher rain fade margins but sub 10 millimetre wavelengths reduce the size and weight of the arrays.

The space to earth link with beam steering combined with narrow or fractional beam widths should deliver several tens of dB of isotropic gain. The user device on earth will also have useful gain assuming either a simple pointed dish or planar antenna (with a maximum gain at 90 degree elevation). Together these gains should be able to support a broadband link equivalent and sometimes better than a terrestrial network of similar channel bandwidth in a similar band.

However the cost of this gain needs to be calculated and is a function of the weight and size of the antenna array in space and the active and passive components in the RF front end of the space based transceiver.

Historically the usual choice for power amplification in space has been the Travelling Wave Tube Amplifier (TWTA). Developed in the Second World War for military aviation radar, TWTA devices today are capable of delivering between 10 watts and 10 kilowatts up to 1 THz but are heavy, fragile and expensive.

With every kilogramme costing thousands of dollars to launch into space it is not surprising that weight is an important part of the installation cost equation.

GaN HEMT devices have been used as a solid state alternative in Ku band for the last 15 years or so and are now generally competitive. A 750 watt TWTA weighs 37 kg and draws 2.5 kilowatts of power. A 400 watt Ku band GaN device weighs 30 kg and draws 2.2 kilowatts. It is expensive relative to GaAs but inexpensive relative to a TWTA. CMOS is a non-starter for these higher frequencies. For comparison, GaN has a maximum power density of 4000 Mw/MM compared to 100 Mw for CMOS. Note than antenna arrays will need separate power amplifiers (and LNA's and filtering) for each element or group of elements.

LNA's for the Ku and Ka band receive path are now typically GaAs with a gain of 11.4 dB at Ku band and 9.5 dB at Ka band with a noise figure of 4 dB at Ku band and 6.9 dB at Ka band. At C band a similar device would yield 15.5 dB of gain with a 3 dB noise floor.

Similarly on the filter path, designers of FR1 4G and 5G user devices are able to source SAW and FBAR filters with a Q of 5000 though even FBAR filters struggle at the upper end of the band.

The only device that could equal this selectivity at Ka band would be a Wave Guide. For comparison, on chip filtering delivers a Q of about 20, a PCB strip line 100-150 and ceramic filters 300-500. Techniques such as Microstrip are vulnerable to signals propagating around the filter. PCB production tolerances can shift the pass band and/or create a noise and or power mismatch and several dB's of insertion loss. In practice, achieving a sharp clean roll off closer than 1 GHz from the pass band is ambitious.

It is therefore a familiar story in which the RF stages of a user device and or CPE equipment at these higher frequencies are noisy and inefficient and inconsistent all of which adds up to a loss of network performance and increased network cost.

As a rule of thumb, increasing the oscillation frequency of a network from 3 GHz to 30 GHz (a decade) increases phase noise by 20 dB and decreases power amplifier power and efficiency by 20%. Note that local oscillator noise floors have an increasingly large impact on EVM as bandwidths exceed 100 MHz. The gap between modelled, measured and actual performance will increase and the variability of performance from device to device and batch to batch will get bigger.

Last but not least high frequency networks potentially deliver multiplexing capacity and throughput gain from wider channel bandwidths, 400 MHz for 5G FR2 or 250 MHz for Ku and Ka band satellite. However this comes with an associated ADC and DAC power and performance cost.

Analogue to Digital Converters are compared using a figure of merit (FOM) for power efficiency.

The FOM envelope remains constant for sampling frequencies below 100 MHz but for every doubling of bandwidth there will be a doubling of required power. Above 100 MHz there is an additional 10dB decade penalty so a doubling of bandwidth increases power consumption by a factor of 4. Digital to Analogue Converters do not generally use iterative processes and are therefore simpler and less power hungry but the same ratio increase applies.

The summary message is that noise and gain budgets become increasingly important as frequency increases. Remedies can be expensive, realisable in military radio but hard in networks with ambitions to meet mass market consumer price and performance expectations which include servicing low ARPU markets.

Last but not least there is an issue of scale.

The RF efficiency of FR1 4G and 5G smart phones is a function of market volume. A market of billions of devices supports the R and D and manufacturing investment needed to deliver high Q low insertion loss SAW and FBAR devices, efficient and effective power amplifiers, LNA's and other RF sub systems.

FR2 5G starts by definition with zero scale, adds cost and reduces performance due to real estate and power constraints in existing FR 1 user devices. Users complain about power drain in FR1 5G and are unlikely to appreciate the higher power drain implicit in an FR2 device.

If the satellite industry seriously expects to serve consumer markets then they have the same problem only more so.

The Taiwanese sub-contractor building Starlink Consumer Premises Equipment (CPE) has a turnover of $2 billion dollars. The Taiwanese sub-contractor building the iPhone has a turnover of $200 billion dollars. RF scale drives R and D and manufacturing investment but also helps tighten production tolerance which in turn improves RF performance – it always has, it always will.

Noisy devices translate into noisy networks. Noisy networks make it hard to deliver consumer value. Reducing noise is hard but is helped by market scale where the terrestrial 5G industry has significant advantage.

It is going to cost $10 billion dollars to get a high count Ku and or Ku band LEO constellation fully operational and commercially competitive. Getting low noise high performance devices into the hands of consumers is going to cost an order of magnitude more but would be easier if the terrestrial and space supply chains became more closely coupled.

In the grand scheme of things this is a trivial amount of money. China has built 700,000 5G base stations this year and has a stated aim to spend $280 billion on national roll out. China is a big country but is only 5% of the world's land mass which is only 30% of the world's' surface area.

A couple of hundred billion dollars for a **global** space network combining broadband connectivity with positioning and imaging looks like a comparative bargain.

Adding synchronous services further increases this value, a topic which we address over the next few months…….

Ends

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