RTT TECHNOLOGY TOPIC
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Millimetre Metrology

On June 3rd 1769 George 3 and astronomical friends stared up through an unusually clear sky to observe and time the transit of Venus from the Kew Observatory near Richmond.

In parallel Captain Cook sailed to the South Seas to make the same measurement from Tahiti returning with New Zealand and Australia as a gift for the King.

These and other transit measurements (Mercury), established the distance between the Earth and the Sun and the Earth and other known planets within the solar system within an accuracy of 2%.

In November 1967 from her shed at the Mullard Radio Astronomical Observatory just outside Cambridge, Jocelyn Bell noted a repeating series of radio pulses spaced just over a second apart.

This was the first observed pulsar and was to be the path to a deeper understanding of the dimensions and dynamics of the Universe.

In 1895 in Calcutta, JC Bose generated a radio carrier at 60 GHz triggering a small explosion and ringing a bell a mile away.

The point of these three separate but linked examples is that George 3 and Jocelyn Bell were able to measure their observations using simple but accurate clocks.

JC Bose was able to calculate wavelength from the dimensions of the wave guides and horn antennas and semi conducting crystal detectors used to transmit and receive the carrier wave but the frequency had to be inferred as there was no measurement apparatus available.

120 years later, measuring the millimetre band can still be problematic and cause difficulties for design teams developing and optimising millimetre band RF front ends for 5G and satellite user devices.

Partly this is due to the increase in noise and matching losses at higher frequencies and partly due to the need to measure and optimise beam forming and beam steering multiple antenna arrays in 5G and satellite RF front ends.

As a reminder,***beam forming** spatially multiplexes users together within a cell, sharing the same frequency and time resources and using pre coding to keep separate user streams apart. This is also known as MIMO (**M**ultiple **I**nput **M**ultiple **O**utput or for systems with more than 64 elements in the array, **MASSIVE MIMO**. Beam forming requires precise real time channel state information (CSI) and full digital control of the phase and amplitude of every antenna element. The main objective of MIMO beam forming is to increase capacity.

Beam steering directs narrow dedicated beams towards a user and can be used to increase throughput per user or achieve longer range by increasing flux density and signal to noise ratio. Some nulling of interfering signals can also be achieved on the receive path. Beam steering can be realised with relatively simple analogue phase shifting of each antenna element.

In a line of sight channel with several users in different locations, beam forming will simultaneously generate a beam towards each user similar to beam steering. In a scattered channel, beam forming will generally deliver more capacity than beam steering.

Beam steering will deliver range gain in line of sight conditions, for example to and from a satellite directly overhead and can be used to form virtual cells of terrestrial coverage. 5G terrestrial beam forming is usually deployed as TDD as the transmit and receive path are reciprocal. This simplifies channel sounding.

Satellite radios links are typically FDD as this improves receive sensitivity. If TDD was used, round trip delay would introduce unacceptable inter symbol interference and/or require excessive time domain guard band overhead. Co sharing terrestrial 5G TDD and satellite FDD in Ku and Ka band therefore requires precise spatial separation.

Theoretically narrower beam widths mean that more users can be supported within a given amount of spectrum within a certain amount of 3D space. Directional gain should increase individual user throughput and some capacity gain can be achieved by having smaller cells.

Antenna arrays with a beam width of less than one degree are described as fractional beam width. A 0.7 degree beam at 40 GHz delivers approximately 44 dBi of directional gain. An array of the same aperture at 70/80 GHz with a 0.35 degree beam width increases the directional gain, as you would expect, by 6 dB and allows the RF signal to be sent to specific small geographic areas as and when required. Beam allocation is cell specific whereas in 5G it is user specific.

A V band high count LEO constellation at 1200 kilometres could for example be configured to provision thousands of cells with a radius of 8 to 11 kilometres. Fractional beam width antenna arrays in space in lower orbits could realise smaller cells and relatively dense terrestrial frequency re use though less dense than terrestrial 5G where inter site distances of 100 metres to 400 metres are not uncommon. A high gain RF down link from a satellite could however be destructive to a spectrally adjacent terrestrial 5G TDD receiver front end. Potential capacity gains from spectrum sharing could therefore be compromised by inter-system interference.

Note also that as beam width reduces, phase or amplitude distortion will become progressively problematic (and harder to test - see below). There will also be a bigger difference between the theoretical performance of the antenna array and its real life performance (usually described as implementation loss). This means testing becomes more important (see below).

In 5G FR2 Ku and Ka-band 5G, the channel is typically sparse with only two or three significant line of sight or non-line of sight paths to the user with non-line of sight exhibiting high losses from surface absorption. FR2 massive MIMO systems are therefore more likely to employ hybrid beam forming where instead of having one RF chain per element, the array is sub divided with each group having its own RF chain with final beam steering done by analogue RF phase shifting. This reduces hardware cost and complexity and CSI overhead.

But it does not reduce test complexity.

2G tests of base stations and user devices were all cabled.

Cabled testing however does not capture how well or badly an antenna system is performing. 3G therefore introduced radiated performance requirements for measuring/estimating antenna efficiency.

4G introduced test regimes for base station active antenna systems and user device MIMO.

5G FR1 (<6 GHz) is similar to 4G but with extended UE MIMO testing.

5G FR2 (>6 GHz including the millimetre band >30 GHz) is entirely specified and validated using radiated Over the Air (OTA) connections with transmitter performance specified as equivalent isotropic radiated power (EIRP) which is measured in a specific direction unlike previous transmitted radiated power measurements which are a 3 D average. The receiver similarly is measured as equivalent isotropic sensitivity (EIS).

The 3D test involves rotating the phone until a peak EIRP is measured. Other EIRP outputs are described as spherical coverage tests. The UE has to be beam locked while these tests are done.

Note that in an FR2 smart phone, there is an expectation of 7dBi of downlink peak gain. This implies that this is an important parameter to measure with implications for 5G terrestrial network performance and network economics.

However there is an order of uncertainty of about 7dB as to how these metrics are measured. Additionally there may be up to 13 dB of hand loss depending on where the antennas are mounted and other issues like ground plane and matching loss under conditions of variable capacitance. These test uncertainties are compounded by differences in radiated path loss between near field and far field measurement methodologies. This level of test ambiguity should be worrying to anyone interested in the economics of 5G and satellite networks.

The message is that George 3 knew what he was measuring, how to measure the observation and how to make calculations based on the measurements.

It was of course nice to know the dimensions of the solar system but it was never going to be an option to improve its performance.

Likewise Jocelyn Bell unlocked our ability to comprehend the dynamics of the Universe but without the prospect of changing it in meaningful ways.

Millimetre testing might be more mundane but has immediate (and long term) monetary implications for the 5G and satellite industry.

A subject that surely deserves more scrutiny?

*Thanks to Moray Rumney for sharing his presentations for Keysight Technologies on the differences between beam forming and beam steering.

Ends

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