Electronic Beam Scanning for 5G with a Rotman Lens
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Introduction
There is much hype about 5G at present but as yet there are no standards or internationally agreed platforms as to how the next generation of mobile technology will shape up. What we do know is that it will be radically different from what we have today which have been incremental steps in evolving mobile technology. Consumers have a growing and insatiable appetite for data and that translates to devices and supporting backhaul requirements for very wide bandwidths and high levels of complex QAM IQ modulation. This means that devices and platforms will need to be at millimetre wave because only there can the high bandwidths necessary be implemented.

Different manufacturers are promoting different frequencies; 28GHz, 50GHz, 77GHz or even 102GHz. Who knows which frequencies will be chosen? What seems certain is that 5G will be a fully seamless and integrated network. For example, when in a city the mobile signal maybe picked up; when in the countryside or at sea the satellite will maintain continuity and as a user steps into a building, the mobile device will start receiving from a Wi-Fi access point without the user even noticing or having to log-on. Whilst many things are uncertain, major infrastructure and developments are occurring that enable some conclusions to be drawn:

1. Several companies are planning to launch networks of low earth orbit (LEO) satellites or mega-constellations. These are likely to be at Ka band to get high data throughput and acceptable levels of atmospheric absorption. These satellites will appear for 10-15 minutes before the device needs to switch over to the next one.
2. Wi-Fi is likely to be at 60GHz where there is a very high level of atmospheric absorption and so the signal does not travel that far. At this frequency, 4GHz bandwidths which transform to up to 15Gb/s data rates are feasible.
3. Backhaul is likely to be at 94GHz because here the opposite of 60GHz occurs and a transmission window will allow the same data rates at up to 15km distance.
4. Mobiles will need to be satellite, Wi-Fi and network enabled and the real unknown is as to what will be the chosen frequency for the network.

Properties of Millimetre Waves
The name gives a clue in that the wavelength is very short; that means small devices, small antennas and light weight. A 4G phone at 2.1GHz will have far less atmospheric absorption than a 5G phone at 77GHz so there will be a need for thousands, rather than hundreds of access points or base stations. Moreover, the beams are very narrow so beam steering technology will become critical. This article describes a very special and inexpensive means of beam steering at millimetre waves.

The Rotman Lens
This was first designed by Rotman and Turner in 1965 and was aimed at relatively low frequency radar applications (3GHz). It works by reflections in a ‘lens’ having phase shifts such that the direction of the output array transmission depends upon the input direction of the incoming beam. With careful design, gains of 10-15 dB are possible.

The Rotman lens features a number of input (or beam) ports, a lens cavity, and a number of output (or array) ports, which are each connected through ‘phase correction’ lines to a radiating element in an antenna array. When the lens is excited at one of the beam ports a tilted beam is radiated from
the array. By switching between input ports, the radiated beam can be scanned through the lens’ field of view.

To achieve a high angular resolution between beams, a large number of beam ports are required. This can lead to a requirement for a high component count on the input side of the lens, as well as high spill-over losses due to small port widths (spill-over loss occurs when some of the signal being transmitted between the lens beam and array ports is incident on the sidewalls of the lens which are lined with absorber or dummy ports to prevent internal reflections; this causes a loss of signal power). The Arralis design includes a method of improving the angular resolution of a Rotman lens beam forming network whilst reducing the component count and system losses, without causing any significant change to the overall size.

The geometry of a conventional Rotman lens is shown in Figure 2. A number of input (beam) ports are situated along a focal arc at one edge of the parallel plate region, with a number of output (array) ports located on the opposite edge. The array ports are connected to an array of radiating elements (or antennas) through phase correction lines of unequal length. When the lens is excited at one of the beam ports, a signal propagates through the parallel plate region, is sampled by the array ports, and transmitted via the phase correction lines to the array elements which radiate the signal into free space. The propagation path lengths from the beam port under excitation to the antenna elements provide a progressive linear time delay across the array. Due to constructive interference, a delay of Δt between adjacent elements, separated by a distance of N, produces a radiation pattern at a scan angle, θs, relative to the central axis.
\[ \theta_s = \sin^{-1}\left(\frac{c}{N} \Delta \tau \right) \]

Where \( c \) is the speed of light in free space. The lens is a true time delay beam-former: the values of \( c \) and \( N \) are constant, and the beam scan angle depends only on the time delay \( \Delta \tau \). Providing \( \Delta \tau \) is independent of frequency (as in TEM transmission mediums) or has only a weak dependency (as in so called quasi-TEM transmission mediums such as microstrip), the scan angle does not vary with frequency, as is the case with phased arrays. The lens features three focal points, \( F_1, G, \) and \( F_2 \), which when excited form radiation patterns with peaks at \(-\alpha^\circ, 0^\circ,\) and \(\alpha^\circ\) respectively. Rotman lenses are known to those with knowledge in the field.

Figure 2
Parallel plate region
Phase correction lines
F1
F2
Circular focal arc

Figure 3
Actual Arralis 94 GHz Rotman Lens measures only 7cm long
Retrodirective Operation

For the ‘5G’ applications, the Rotman lens can be an ideal retrodirective antenna. This means that when the signal is received from one direction, it can automatically transmit back to the same direction without physical movement or complicated circuitry and the arrangement is instant. Imaging a WIFI access point in the corner of a room that receives a transmission from an angle of 30 degrees, it can immediately align itself and transmit back in the same direction. Another example is following a LEO satellite as it moves across the sky in a period of 10-15 minutes. The connected device on the ground can ‘lock-on’ and stay with the satellite throughout. Even more significant is if the receive antenna is located on a vehicle which is moving and turning, it will constantly maintain alignment with the satellite. When a new satellite appears on the horizon, the signal is acquired again, automatically and with an unnoticeable time delay.

At millimetre wave frequencies, the lens is best constructed in a waveguide structure to avoid losses into the substrate. This also requires very careful and precision machining; in particular, the array waveguide paths must be phase matched or the effect upon the phase array will be high side-lobes or poor directivity. The ‘spill over’ areas, as mentioned before, either have to be absorbed, that is lined with an RF absorbing material or, as is common at microwave frequencies, be terminated at 50 ohms. Another great advantage of the Rotman lens is that its topology is essentially flat which makes it ideal for vehicles and aircraft.

Summary

The future evolvement of ‘5G’ with all its demands for high data rates implies broad bandwidths and millimetre wave devices and systems. The properties of millimetre waves breed the requirements for beam steering antennas. The Rotman lens is one solution that can satisfy many applications.
References:


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