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Antenna Array Analog Processor for Emerging Wireless Paradigms

(Keynote)

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Abstract - In this paper some of the possibilities that analog signal processing afford towards realising lower power consumption low latency solutions in emerging antenna array wireless systems are discussed. It is shown how an analog processor can be realised to construct radios that are can be used in propagation difficult, and enhanced trust systems. The approach permits operation with real time analog processing which is not unduly throttled by the power consumption and data throughput limits associated with current digital signal processing hardware.

I. Some Working Definitions

This Passive antennas provide spatial and spectral filtering as well as impedance transformation to/from a circuit environment to/from free space.

Processor antennas include the functionality associated with passive antennas but in addition admit the possibility for signal processing on transmit, or upon receive, using additional components that can be intrinsic or extrinsic to the antenna radiation element(s).

II. Setting the Scene

The concept of wireless systems endowed with intelligence that allows them to perceive changes in their environment and adapt their parameters in order to maintain a high quality of service would be of exceptional value in low cost ubiquitous wireless systems. Ideally;

(i) the radio assesses and mitigates any deleterious effects that the external electromagnetic environment within which it is expected to operate,

(ii) the radio automatically beam forms in order to optimise its sent and receive data at high quality of service in a secure low latency manner.

These requirements provide a stimulus for innovative antenna array architectures capable of operating in real time.

Multiple-antenna (MIMO) technology is becoming more widely used for wireless communications. Its use is predicated on the observation that the more antennas the transmitter/receiver is equipped with and the more possible signal paths available within the propagation channel the better the overall the performance will be in respect of data rate and link reliability. This has the potential to yield improvements in throughput and simultaneous scheduling of a large number of user terminals provided orthogonal propagation channels and the means to excite them exists.

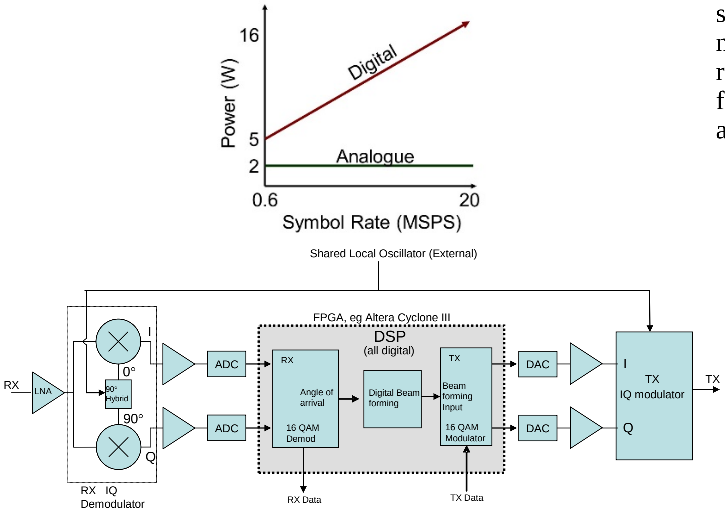
The above suggests, on the plus side, the possibility for the exploitation of extra degrees of freedom provided by the multiplicity of available antennas. While on the negative side there is a price to pay in terms of increased complexity of RF hardware, energy consumption, and signal processing overhead. An additional important consideration is how one can intrinsically incorporate secure data transfer at the fundamental physical layer level at no additional cost.

Several approaches have been developed by the author in order to try to offset these overheads and to harmonise the theoretical framework in which such novel antenna systems can be developed in order to achieve specific operating specifications, [1-4]. Some of these are discussed below.First, confirm that you have the correct template for your paper size. This template has been tailored for output on the A4 paper size. If you are using US letter-sized paper, please close this file and download the file “MSW_USltr_format”.

III. Antenna Array Techniques that Use Analog Realtime Signal Processing

These are antenna arrays with signal processing capability used to identify spatial and/or temporal signal characteristics such as the direction of arrival, and use this to automatically beamform in order to track and position high directivity beam(s) onto roaming mobile device(s), i.e. retrodirective action.

Real time signal processing at ultra-high data rates such as those envisaged for example for 5G, >Gbytes/sec with low latency, is exceedingly demanding on digital signal processing hardware capability and power consumption. Fig 1a shows how the power consumption associated with a 5 x5 digital beam former constructed on a FPGA scales as a function of even moderate symbol rate when executing the digital portions of the architecture shown in Fig.1b. The arrangement in Fig.1 b could be used form a single cell in a classical phased array or in the self-tracking or directional modulation geometries discussed later in the paper.



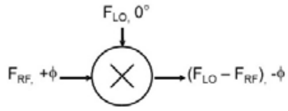
(a) Power consumption (b) Digital unit cell processor

Fig.1 25 element Digital beam former unit-cell power consumption

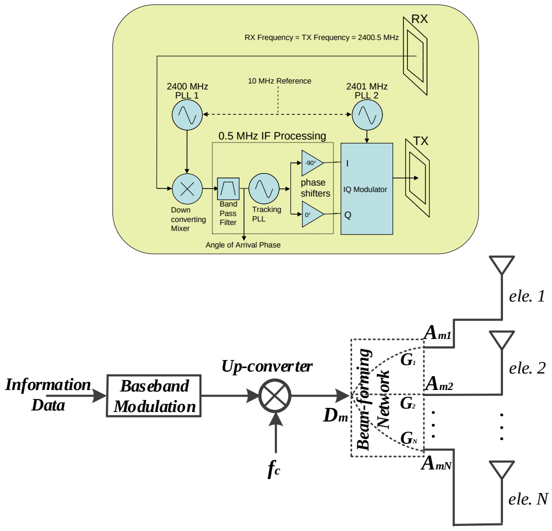
On the other hand analog computers, which have been around in mechanical form for over a millennium, Fig.2a and in more recently in electronic form, Fig.2b, can provide real time signal processing at beyond Gigabit/sec data rates in real time and with extremely low power consumption overhead.

Fig.2 (a) The world's oldest known analog computer the Antikythera mechanism, 150 - 100 BC
(b) Analog computer

The key operation needed for real time signal processing is the mixer, shown in Fig. 3a in down conversion mode. In this embodiment the down converted signal contains conjugate phase information. Appropriate signal mixing can be used as the basis for real time RF analog signal processing operations. In reality due to mixer leakage and port isolation issues more sophisticated versions are used when high performance is needed. For example, Fig.3b shows both the transmit and the receive analog functional architectures necessary for actual field usable phased array operation, c.f. Fig.1b digital transmit architecture.

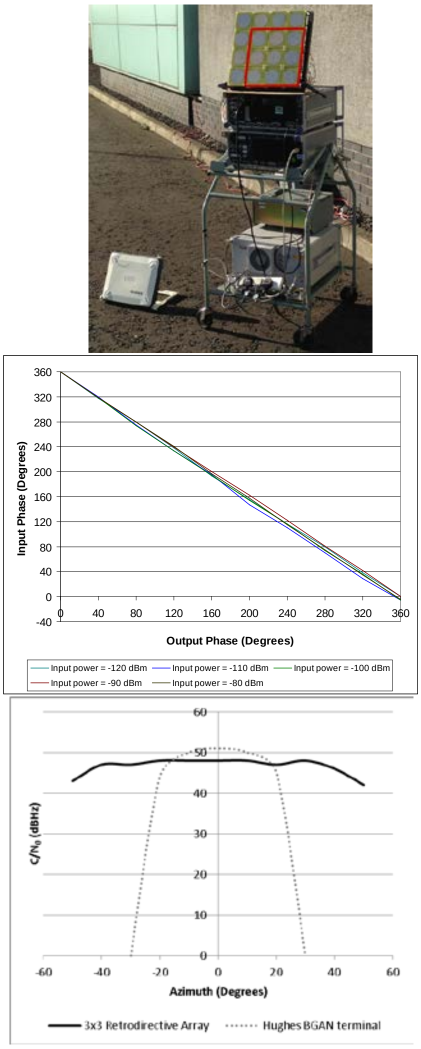


(a) down converting mixer



(b) analog processor with data extraction, insertion capability
(c) phased array transmitter
Fig.3 Core Real Time Signal Processing Technology

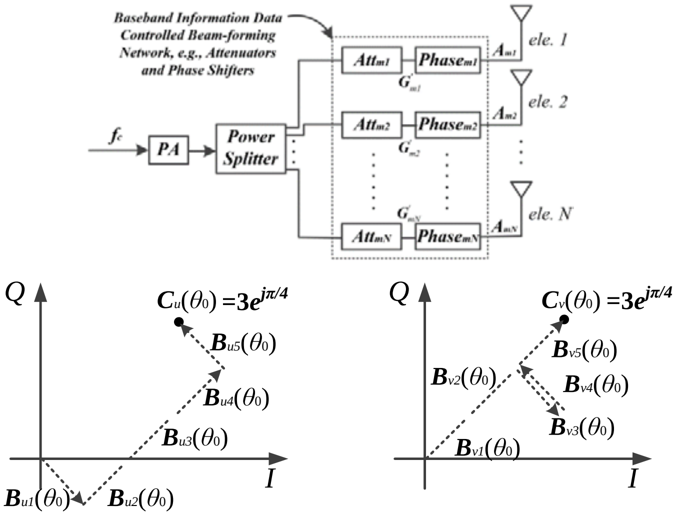
Fig.4a shows a 3x3 element SatCom terminal constructed using the analog conjugation approach. The system can acquire without any manual intervention a live Inmarsat global beam signal within a few milli-seconds and continue to track it as the antenna array yaws, pitches and rolls within prescribed limits. The operation of this system is predicated on the down conversion properties of the mixer in Fig.3a with the arrangement in Fig. 3b being capable of producing very linear phase conjugation, Fig.4b. Phase conjugation operation permits automatic maximal power combining on receive as well as automatic signal re-transmission to a known pilot location which self-compensates for multipath differential phase effects permitting coherent spatial recombination in mobile scenarios, i.e. mitigates to a large extent unfavourable propagation path phase characteristics, Fig.4c.



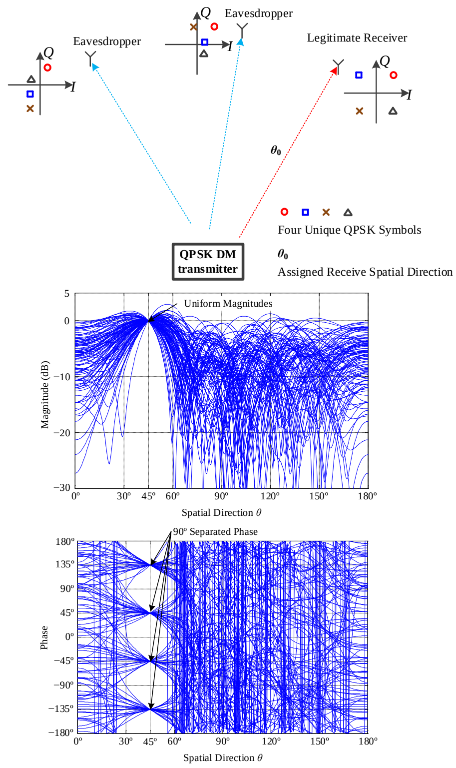
(a) Terminal (b) phase conjugation response(c) off-air result

Fig.4 3x3 element self-tracking SatCom terminal

Additionally wireless systems secured in the physical layer without the aid of mathematical encryption can be created. This approach evokes the recent principle of directional modulation, [4],[5], realised through subtle architecture variation of the architecture in Fig. 3c, to that of Fig.5a. Here instead of encoding the transmission data from a single coherent source and applying it to all of the radiating elements in the array as in the classical phased array, the data is now encoded as a unique vector across the array elements on a pair symbol basis, Fig.5b. As a result the modulation can only be successfully decoded along a specific spatial direction, i.e. a level of secure communication has been achieved at the fundamental physical wavefront layer, Fig.5c.



(a) Directional Modulation Architecture (b) per symbol vector encoding



(c) Spatial selective data transmission

Fig. 5 Directional Modulation Physical layer Secure Radio

IV. Antenna Element Considerations

Consider now what special characteristics if any the radiating elements in the systems described above must exhibit. For the directional modulation case the characteristics of the antenna and the array are equivalent to those of any standard phased array in regard to polarisation type/purity, element spacing, impedance match, etc.

For self-tracking application again the above is broadly true, however there are two important features that must be taken into account. The first is that each radiating element must exhibit low gain, i.e. have wide field of view. This property is primarily what allows the retrodirective array to have a flat monostatic response over a wide spatial range. Second, for SatCom applications such as Ka,Ku band satellite data communications, Table 1, the element must additionally be circularly polarised and ideally should exhibit low axial ratio over as wide a range of elevation angles as possible. The reason for this is that for reliable mobile operation, from a banking aircraft to a satellite for example, or for operation at high latitudes then axial ratio must be preserved.

Top level specification

Low profile high-gain Ka Ku band antennas for aircraft to satellite data communications.

Transmit in the 29.0–31.0 GHz ; Receive in the 19.5–21.2 GHz

Ideally:
The antenna shall consist of either a single combined transmit/receive aperture;

Scan the beam electronically in the elevation range from -10 to +95° and full 360° in azimuth;

Overall mechanical envelope of the antenna system < 23 cm

Transmit gain of the antenna 35 dBi; Receive gain of the antenna 35 dBi

Antenna G/T > 10 dB/K;

Transmit and receive polarizations shall be orthogonal circular
Axial ratio < 2 dB within the ±2° cone off boresight, for all scanned beams;

Antenna mass < 25 kg including radome.

Table 1 Ka Ku Band Satellite Communication

This gives rise to set of vary challenging demands on the radiating element as conceptualised as in Fig.6. One way we have addressed the situation is to develop a radiating element which embodies the qualities identified in Fig.6. This can be achieved in a relatively simple way by employing two know technologies, one old, and one relatively new. Here we use a set of crossed ‘fat’ elliptical dipoles phased for the correct hand of polarisation through an exterior 90^0 hybrid (the old), then we position these over an artificial magnetic conductor ground plane (the new), Fig.7a. This allows the arrangement to be low profile while preserving a reasonably wide impedance match, and reasonable half power beam width at low axial ratio, Fig.7b. The resulting radiating element was then tested for both its monostatic and bistatic far field radiation patterns which show that it is capable of operating over 120^0 in azimuth, Fig. 7c.

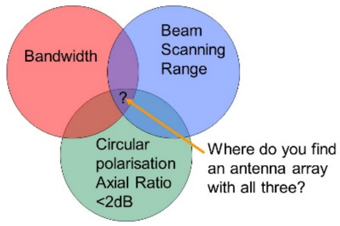
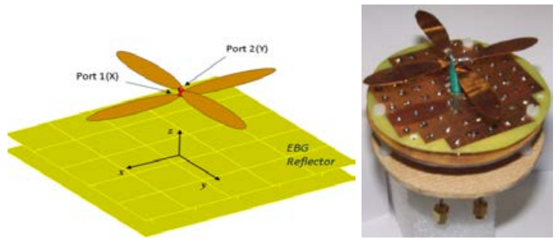
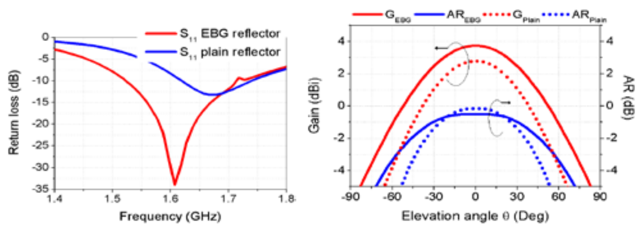


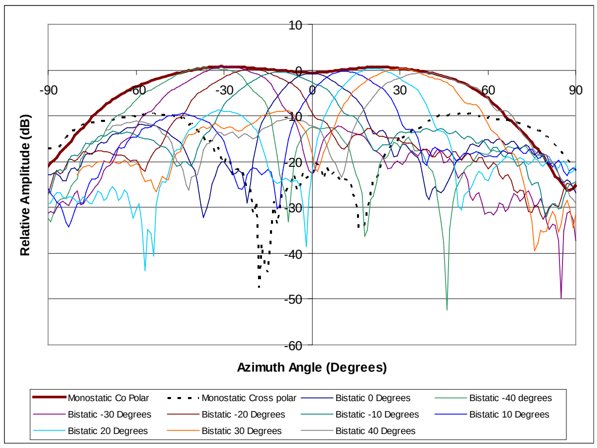
Fig.6 Radiating element consideration



(a) crossed diople over groundplane



(b) properties of scaled frequency antenna



(c) Monostatic and bistatic response

Fig. 7 SatCom antenna element

V. CONCLUSIONS

This paper has shown that simple analog circuits involving mixer technology can be used to advantage in order to replace, or, to off-set the computational load and power consumption associated with conventional DSP solutions in wireless systems where high throughput and low power consumption foot print is required. The result of the application of this approach that multi- antenna wireless systems of significant complexity and with advanced functional capability suitable for deployment in mobile scenarios were power consumption and mass is a premium can be readily constructed largely from pre-existing COTS circuit components.

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