Abstract

A fully digital wideband multibeam steerable antenna array is being developed by SatixFy. The structure and architecture of the digital beamforming chipset and of a full array based on it was presented in [1]. The performance and limits of such an antenna array were presented in [2], shows the feasibility of a fully digital design for a variety of applications in the satellite communication field. In [3] the actual chipset and antennas were presented along with measurement results using the actual production chips. In [4] real-time performance measurement results of a digital electronically steered multi-beam 256 element antenna system (ESMA) are presented for static and mobility conditions.

This paper presents special ways in which digital processing, as shown in [1]-[3], can be utilized to make use of the antenna aperture. In particular, we refer to two techniques:

- Optimal receive beamforming with a digital beamformer
- Polarization control for multibeam

Beamforming on receive is typically achieved by properly delaying the signals arriving from a given direction such that they coherently combined in a well-known direction. However, pre-defined delays, phases and gains per element do not necessarily provide the optimal way of combining the desired signal. Different noise and interference levels at different elements may require different weights per element, which are to be measured at the receiver. The paper describes beamforming algorithms, which are very similar to diversity combining mechanisms, that are optimized for this operation.

When multiple beams are to be transmitted or received, from the same aperture, polarization, with respect to the aperture orientation might be different for each beam, even if the signals themselves have a distinct polarization. Doubling the transmit/receive chain per element, for example, for both vertical and horizontal polarizations, would provide a full solution, but at the expanse of doubling the cost of the array and its power consumption. In the paper we present a solution that uses a single RF chain per element, that makes it possible to control the array polarization at the expanse of slightly enlarging the array size.

1. Introduction

Near-future mobile wireless communications require high data rate systems with virtually, worldwide coverage. Due to the insufficient coverage provided by terrestrial networks, high data rate services are usually not available in remote areas, or on board of ships and airplanes. Satellite communications (SatCom), and more specifically SatCom on-the-move (SOTM) are thus key in achieving high-capacity communications with a global coverage. With recent explosion in large capacity wireless access systems demanding high spectral efficiencies, array antennas have now assumed great significance in radio and wireless communication system. Multi-Input Multi-Output (MIMO) antenna arrays has now become an integral part of the standards for cellular and wireless local area networks in current and future generations. These active antenna arrays will play an equally important role in next generation high throughput-satellite (HTS) communications. Also, with the introduction of large LEO and MEO constellations being planned by companies like OneWeb, SES, SpaceX, Telesat and others, there will be a growing need for antennas at ground terminals tracking multiple satellites. The parabolic dish antennas have been de-facto satcom earth station antenna thus far because of mostly fixed pointing for GSO applications. These antennas have their advantages from cost and power consumption but also are extremely inflexible and have lower efficiencies. On the other hand, electronically steerable antennas are active scanning antennas that provide many
benefits viz self-installation capabilities, multi-satellite communication and satellite tracking. Payloads can be made more flexible and enable techniques such as multibeam, beam hopping and flexible beam shaping. All – electronic control removes the need for moving mechanical parts, which are slow and more prone to malfunctions. At the present time, Ku-band capacity is widely available among the existing geostationary satellite networks already orbiting the planet, hence, increased interest has been addressed to satellite services at Ku-band, namely, digital TV broadcast, broadband internet services, internet-of-things (IoT), etc. The success of these services however, will depend on the development of new high performance and low-cost user terminals, with the ability of tracking the satellite position while in motion. More specifically, the antenna employed, must be capable of very wide-angle scanning whilst keeping the fabrication costs as low as possible, as most applications apply to mass consumer markets. For low cost applications such IoT, cost of antenna can be further reduced by using energy efficient waveforms such as half-duplex which optimize the link and resource utilization. Cost impact of such a waveform can be realized by designing single antenna that can serve both as Rx and Tx.

In this paper, we provide an overview of Beamforming and different implementations, with focus on some salient advantages offered by digital beamformer in a more practical operational environment. Most analysis and literature for beamformers often make assumptions on thermal noise from the RF chains being similar in power across all elements, overlooking the practical considerations such as part to part variations and impact of temperature. Digital Beamformer inherently provides an architecture that's best suitable for optimal array processing with tremendous flexibility. Section 4 covers this in more detail. Additionally, polarization control is another practical feature that does not receive as much attention. Need to support multiple polarizations for multi-beam reception or transmission has big impact on cost, power and complexity of the HW. Again, digital beamformer provides a good platform to make the tradeoffs to support this feature.

2. Beamforming Overview

Antennas are fundamental enablers for wireless communications. Each antenna, acting as conversion of electric signals into electromagnetic transmissions or vice versa is associated with a radiation pattern which corresponds to the energy radiated by that antenna. An antenna’s gain and directivity go hand in hand. The greater the gain, the more directive is the antenna. It is this feature of the antenna that has become focus of exploits for meeting the increased capacity requirements over the years and more so now in the next generation wireless communications both in terrestrial 5G and satcom.

Beamformers are an array of antennas which can control the radiation pattern in order to make the antennas directive through controlled constructive/ destructive superposition of signals from different antenna elements. Beamforming in general can be classified into two broad categories: passive and active. Passive beamformers, as the name suggests, are fixed directive antennas made of passive components such as transmission lines that has beam pointing in a fixed direction.

On the other hand, active antennas employ active components namely phase shifters for each antenna to dynamically steer the beam. Active beamformers are also popularly known as phased antenna arrays. There are 3 main approaches to beamforming for implementing electronically steerable antennas, as depicted in Figure 1:

i. Analog beamforming (ABF)

Analog beamforming can be further subdivided into following 3 categories

(a) RF beamforming

The phase shifting in RF beamforming is implemented in both Rx and Tx prior to the mixer. Reduced component cost of RF beamforming is one of the key reasons for its popularity particularly in millimeter wave where the small size of the phase shifters also allows better integration in RFIC. However, reduced phase shifter precision as well as degradation in noise figure due to presence of phase shifters are some of the challenges for the performance for such a technique. Additionally,
the phase shifters and the BFN will need to be designed specifically for the RF frequency of operation.

(b) LO path beamforming

Beamforming in LO path using the LO distribution network is another alternative which helps overcome the Noise Figure challenge by shifting the phase shifter from signal path to the LO path. However, it leads to increased power consumption and the complexity also scales with the size of the antenna.

(c) Analog baseband beamforming

The beamforming happens after down-conversion in baseband allowing one to design higher precision phase shifters. However, the size of the phase shifters, as well as the complexity of the beamformer network with mixers per RF chain and network of splitters and combiners at baseband can become serious challenges.

ii. Digital beamforming (DBF)

Digital beamforming is widely recognized as the most flexible solution with high degree of control. Additionally, for receiving and transmitting wideband signals and more importantly for multi-beam applications it is far superior to the analog beamforming. As the name suggests, the beamforming is done completely in the digital baseband and requires RF circuit per beamformer/antenna element. The digital implementation allows treatment of RF impairments per antenna element with greater reconfigurability. But it also implies data converters as well as RF front end for each digital beamformer chain which increases complexity and power consumption. However, with recent advances in silicon processes, the complexity, power and cost impediments have been weakened allowing for implementations conducive for building large phased arrays.

iii. Hybrid beamforming

It can be considered as best of both worlds – analog and digital beamforming. To address the complexity of RF chain per antenna element, two stage beamforming which is concatenation of analog and digital beamforming can provide some reasonable compromise for performance and complexity. Hybrid beamformers can provide some limited multibeam capability but performance is sub-optimal compared to digital beamformers. Each cluster of analog beamformer serves as sub-array for the next level of digital beamforming. In other words, analog beamforming using subarray of elements to form more directive super elements of which the signals are then combined coherently to form the required beams within the digital domain.
The Need for Digital Beamformer

Although the benefits and challenges of Digital beamformer were mentioned briefly in Section 2, we summarize the features which make Digital beamformer an extremely attractive proposition:

(a) Wideband Signal Reception and Transmission

Wideband signal reception and transmission are essential for improving the spectral efficiency of the system and increasing the capacity of a terminal. DBF allow easy implementation of high precision phase shifters and high precision delay compensation (true time delay) which allows the antenna array to operate over a large signal bandwidth without any beam squints. This is explained in more detail in section 4.

(b) Ability to scale to build large antennas

In order to build large antennas, the beamformer should be modularly architected to enable relatively simpler scaling. Additionally, large antennas also need the ability to correct for delays both due to scanning as well as system routing which becomes even more challenging with large antennas, to reduce beam squint. Here again, DBF ideally suited for building such a modular design that can easily scale while maintaining performance.

(c) Support large number of beams

MIMO with multibeam capability is the most the effective way of increasing channel capacity. Also, in satellite communications, this allows simultaneous communications with multiple satellites. In this
respect, DBF provides an ideal framework to support large number of beams using the entire antenna aperture which provides the same Antenna Gain and directivity for all the beams.

(d) Fast Beam Steering

Digital beamformer allows for very fast beam switching and steering in order of microseconds. This can enable fast acquisition, tracking in highly dynamic channel environment, as well as beam hopping for payload antennas.

(e) High Flexibility

Active beamformer with flexible reconfiguration to serve multiple applications such as online calibration, operating in a dynamic sub-array configuration or tight monitoring of processing and synchronization adds a lot of value in terms of reliability and adaptability. DBF by its very nature is extremely configurable and adaptive.

(f) Precise Beamforming and Nulling

Digital beamformer allows very high precision control of phase and gain, which allows fine control of the radiation pattern, including, the side lobes, null depths and null positioning. This can be exploited to precisely form the radiation pattern to meet regulatory masks as well as suppress unwanted directive interference while maintaining high signal to noise ratio.

(g) Antennas based on Conformal Structures

DBF with its ability to calibrate and compensate for phase and delay, allows decoupling of antenna geometry from performance thus making feasible conformal antennas which are not restricted to planar 2-D. Different geometric shapes may be necessary such as hemi-spheroidal 3-D antennas or other conformal shapes can indeed be implemented through modular approach using DBF.

3. Digital Beamformer as an optimal Receiver

While most advantages of Digital Beamformer listed in Section 2 have been covered well in literature as well as explained by authors, one of notable practical advantage of DBF is its ability to serve as an optimal receiver. To substantiate this point, we will first build the basic model. Assuming in an array (linear or planar) with N elements, the signal received at the k\textsuperscript{th} element is given by:

\[ y_k = h_k s + n_k, \quad \text{where } k \in \{0, N - 1\} \]  

[4.1]

where,

- \( h_k \) is single tap channel for k\textsuperscript{th} element, which represents the gain and Direction Of Arrival of the signal
- \( n_k \) is the noise in the k\textsuperscript{th} antenna element

The received signal at all antennas can then be represented as follows

\[ \bar{y} = \bar{h}s + \bar{n}, \]  

[4.2]

As can be seen from (4.1), each element of antenna array serves as spatial sampler of the signal producing an independent copy. Depending on the element separation in an array and hence the mutual coupling, these spatial replicas can be partially or fully uncorrelated. An efficient and optimal receiver, combines these different spatially sampled signals with the objective of maximizing the Signal to Noise Ratio as explained below
Let $\tilde{g} = [g_0 \ldots g_N]^T$, be weights applied to the signal received at each antenna element. Then
\[
z = \tilde{g}^H \tilde{y} = \tilde{g}^H \tilde{h}s + \tilde{g}^H \tilde{n} = \tilde{x} + \tilde{w}
\] [4.3]

where
\[
\tilde{x} = \tilde{g}^H \tilde{h}s \\
\tilde{w} = \tilde{g}^H \tilde{n}
\]
\[
\rho = \frac{E(\tilde{x}\tilde{x}^H)}{E(\tilde{w}\tilde{w}^H)} = \frac{\tilde{g}^H \tilde{h} \tilde{h}^H \tilde{g} \sigma_s^2}{\tilde{g}^H R_{nn} \tilde{g}} \quad \text{where} \quad \tilde{f} = R_{nn}^{1/2} \tilde{g}
\]

Optimal solution requires to determine $g$ such that,
\[
\tilde{g}_o = \arg\max_{\tilde{g}} (\rho) = \arg\max_{\tilde{g}} \left( \frac{\tilde{g}^H R_{hh} \tilde{g} \sigma_s^2}{\tilde{g}^H R_{nn} \tilde{g}} \right)
\] [4.5]

The solution to the above can be found in two ways, either by using Cauchy Schwartz inequality or maximal eigenvalue. Here we use the latter
\[
\rho = \frac{\tilde{g}^H R_{hh} \tilde{g} \sigma_s^2}{\tilde{g}^H R_{nn} \tilde{g}} = \frac{\tilde{g}^H R_{hh} \tilde{g} \sigma_s^2}{\tilde{g}^H R_{nn} \tilde{g}}
\]
\[
= \frac{\tilde{f}^H R_{nn}^{-1/2} R_{hh} R_{nn}^{-1/2} \tilde{f} \sigma_s^2}{\tilde{f}^H \tilde{f}}
\]

where, \( \tilde{f} = R_{nn}^{1/2} \tilde{g} \)

\[
= \frac{\tilde{f}^H R_{pp} \tilde{f} \sigma_s^2}{\tilde{f}^H \tilde{f}}
\]

where, \( R_{pp} = R_{nn}^{-1/2} R_{hh} R_{nn}^{-1/2} \)

Since $R_{hh}$ is rank 1 matrix, $R_{pp}$ is also a rank 1 matrix
\[
\rho_{max} = \frac{\lambda_{max} \tilde{f}^H \tilde{f} \sigma_s^2}{\tilde{f}^H \tilde{f}} = \lambda_{max} \sigma_s^2
\] [4.8]
\[
\Rightarrow \tilde{f} \quad \text{is an eigenvector corresponding to the maximal eigenvalue of} \quad R_{pp}
\]

Since $R_{pp}$ is rank 1 matrix,
\[
\Rightarrow \tilde{f}_o = \tilde{f} R_{nn}^{-1/2}
\]
\[
\Rightarrow \tilde{g}_o = \tilde{f} R_{nn}^1
\] [4.9]

Eq (4.9) is popularly known as Maximal Ratio Combiner which is a matched filter and a noise decorrelator.
We will consider the following two scenarios for the analysis of (4.9):

**Case 1**: All receiving elements have equal but uncorrelated noise power

In this case, \( \{n_k\} \in \mathcal{N}(0, \sigma^2) \)

\[ R_{nn} = \sigma^2 I_{N \times N} \]  \[\text{[4.10]}\]

Substituting (4.10) in (4.11), we get

\[ \bar{g}_o = \frac{\bar{h}^H}{\sigma^2} \]  \[\text{[4.11]}\]

In other words, the optimality is just a matched filter. The matched filter for a single tap channel is simply the phase shifter to add all signals in phase.

**Case 2**: All receiving elements have unequal but uncorrelated noise power and signal is narrowband

In this case, \( \{n_k\} \in \mathcal{N}(0, \sigma_k^2) \)

\[ R_{nn} = \text{diag}(\sigma_0^2, \sigma_1^2, ..., \sigma_{N-1}^2) \]  \[\text{[4.12]}\]

\[ \bar{g}_o = \frac{\bar{h}^H R_{nn}^{-1}}{\sigma_k^2} \]

\[ g_{k}^\text{opt} = \frac{h_k^*}{\sigma_k^2} \]  \[\text{[4.13]}\]

(4.13) is an important relation, which shows that the optimal combiner is one that scales each elements by the SNR before combining.

With MRC combining, the overall receive antenna array SNR is sum of the SNR of each individual antenna element.

\[ \rho_{\text{max}} = \sum_{k=0}^{N-1} \left( \frac{||h_k||^2 \sigma_k^2}{\sigma_k^2} \right) \]  \[\text{[4.14]}\]

In this scenario, if all the elements have identical SNR, the overall gain in SNR corresponds to the array size and hence equivalent to array gain.

In the Figure 2, it can be observed that Maximal Ratio Combining provides better overall SNR compared with Equal Gain combining if the variance in noise figure of LNA increases either due to part to part variation or thermal environment of antenna operation. As long as variation is less than 0.5dB, simple matched filtering will be close to optimal. But it deviates from optimality if the variation increases.
Application of MRC (4.9), requires that noise and gain of each element needs to be known so that elements can be appropriately scaled before combining. One of the key sources of noise is the LNA and any other passive or active RF block in the chain before the signals are combined. While it is easy to estimate the gain of each antenna element as part of antenna calibration, noise estimation of each element can be challenging. The entire system noise is generally captured as system Noise Figure. This Noise figure is a function of temperature and frequency and hence will vary. For large phased arrays, thermal (heat) distribution can result in different operational temperatures which in turn will lead to a distributed thermal noise from each of these elements. Additionally, the noise will also vary due to coupling between neighboring elements. All this makes it very difficult to estimate noise and hence can place an extra stress on ensuring the noise between different elements particularly from LNA is almost identical i.e. very small variation in Noise Figure. This implies stricter screening to contain the Noise variation within a certain small band. Even with this as explained above, the actual noise from each source will vary with operating conditions, which would impose a very strict requirement on heat dissipation.
Figure 3 shows an example of heat distribution across the entire antenna as captured by thermal camera. In this example, the temperature across the antenna varies from $30^\circ$ up to $60^\circ$. The Noise Figure of LNA can easily vary by more than 0.5dB across different elements with such a variation in operating condition. This would imply that Noise power or $T_{LNA}$ will vary more than 1dB depending upon the LNA Noise figure. Under such conditions, MRC will definitely provide better performance and hence increase antenna efficiency.

In Digital Beamformer each antenna element is RF down-converted and digitized, which allows easy and accurate estimation of noise per element. This also allows characterizing each element’s noise contribution keeping all the other antenna chains active but muting their contribution in the digital domain. In other words, the estimation captures noise with coupling in true operational environment. This would then allow a much accurate MRC combining. Hence, in theory, Digital Beamformer allows near optimal performance and therefore higher efficiency compared to Analog systems, which passively or actively combine each element making it difficult to estimate individual noise contribution.

4. Multibeam Linear Polarization Control

Polarization of an electromagnetic wave refers to the oscillation of the wave with respect to its propagation plane. If the electric field of the EM wave varies randomly in time, then the wave is considered unpolarized. Depending on the orientation of the electric field the polarized EM wave can be classified into following 3 categories

a. Linear Polarization – if the electric field is confined to single plane along the direction of propagation

b. Circular Polarization – if the electric field has two components that are perpendicular to each other, equal in magnitude and out of phase with respect to each other by $\pi/2$. The resulting electric field rotates in a circle around the direction of propagation and, depending on the rotation direction, is called left- or right-hand circularly polarized wave.

c. Elliptical Polarization – the electric field of the EM wave describes an ellipse. This results from the combination of two linear components with differing amplitudes and/or a phase difference that is not $\pi/2$.

In this section, we will focus on Linear Polarization which is primarily used in Ku Band for both Rx and Tx. Linear polarization is very dependent on earth terminal antenna’s location and orientation with respect to the satellite. Different beams received from different satellites can therefore have different linear polarizations.

![Figure 4 – Polarization skew for beams received from different Geostationary satellites](image)
Figure 5 shows the high level block diagram for polarization control for both linear and circular polarizations. This can be done in RF or Digital domain for a single beam. However, for multibeam, this circuit along with phase shifters for each element needs to be scaled with the number of beams which makes it very expensive proposition particularly for Analog beamformers. On the other hand, multibeam can be easily supported by Digital beamformer but it requires Polarization control inside the digital domain i.e. taking V and H streams from the antenna element all the way to digital and combine polarization control along with beamforming. While this is an optimal solution it still has following disadvantages when compared to single beam solution:

1. Doubles the number of RF and Digital components and hence impacts cost, complexity and power
2. This optimality for multibeam is suboptimal for single beam
3. Heat dissipation and layout complexity grows as the density of components on the PCB grows.

There are twice the number of components for the same area

Satixfy has developed a novel Multi-Beam Multi-Pol solution which overcomes some of the above disadvantages and provides novel way to process multi-beams with reasonable compromise. This involves splitting polarization control between analog and digital section while maintaining the similar interface between RF and Digital, which helps serve single beam optimally and multibeam with multiple polarizations with an acceptable degradation that maintains power. As shown in Figure 6, the solution includes capturing both the vertical and linear components of the signals, arriving with a skew angle $\alpha_1$ and $\alpha_2$, from different direction of arrivals. With multiple elements, the separation of the signals in the digital domain can be made based on both features.
5. Conclusion

In this paper, we provided an overview of beamforming techniques. While many features and benefits of Digital beamforming are well documented and also covered by our previous papers [1],[2],[3], the focus of this paper was expanding on some of practical benefits offered by Digital beamformer that can improve the efficiency of the phased array antenna as well as support Multibeam Linear Polarization control in an efficient way.

We expect the digital beamforming will pave the path for unlocking digital beamformer’s full potential that can address the future needs of tracking antennas for high throughput satellite communications with cost advantage offered by silicon economics.

References

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