Rationale for and design of a generic tiled hierarchical phased array beamforming architecture

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Abstract— **The purpose of the phased array beamforming project [1], [2] is to develop a generic flexible efficient phased array receiver platform, using a mixed signal hardware/software-codesign approach. The results will be applicable to any radio (RF) system, but we will focus on satellite receiver (DVB-S) and radar applications. We will present a preliminary mapping of beamforming processing on a tiled architecture and determine its scalability.**

The functionality, size and cost constraints imply an integrated mixed signal CMOS solution. For a generic flexible multi-standard solution, a software defined radio approach is taken. Because a scalable and dependable solution is needed, a tiled hierarchical architecture is proposed with reconfigurable hardware to regain flexibility. A mapping is provided of beamforming on the proposed architecture. The advantages and disadvantages of each solution are discussed with respect to applicability and scalability.

Different beamforming processing solutions can be mapped on the same proposed tiled hierarchical architecture. This provides a flexible, scalable and reconfigurable solution for a wide application domain. Beamforming is a data-driven streaming process which lends itself well for a regular scalable architecture. Beamsteering on the other hand is much more control-oriented and future work will focus on how to support beamsteering on the proposed architecture as well.

Keywords— **phased array, beamforming, tiled architecture, reconfigurable, scalable**

I. Introduction

Beamforming, as the name implies, is about forming an electromagnetic beam into a certain direction, i.e. it makes a transceiver directional. An example is a light-beam from a spotlight. Directivity can be achieved by using a directional antenna, such as a dish antenna, or by using multiple antennas in an array as will be explained in the next section. Beamsteering refers to changing the direction of the formed beam. Beamsteering can be achieved mechanically by moving the antenna or by changing the path length from each antenna in case of an array. Changing the path length results in changing the phase of a sinusoid signal, therefore these kind of arrays are called phased array systems. Practical reasons allow only a discrete number of different path lengths for the mechanical beamsteering option (for each path length a different cable is needed). [3] With electrical beamsteering, this restriction can be relaxed, allowing faster and more flexible changing of the created beam. Smart antennas refer to systems which determine the direction of arrival (DOA) of a signal by using signal processing. Switched beam systems choose between a number of pre-determined beams while adaptive arrays allow for complete flexibility in steering the beam. [4]. This is summarized in table I.

Exploiting directionality of a transceiver is an obvious way of improving the performance of a radio (RF) system. This is because less energy is wasted sending the signal to all directions or being sensitive in all directions requiring a larger signal. Sending only to the direction of the receiver also reduces distortion to other receivers. Receiving only from the direction

TABLE I
Beamsteering for different antenna options

Antenna	Steering
Directional antenna	
Omni-directional isotrophic	-
Parabolic reflector (dish)	Mechanical
Aperture	Mechanical
Multi-antenna transceivers	
Array	
Fixed plane	Mechanical
Phased array	
Selectable path length	Mechanical
Phase delay filter	Electrical
Smart antenna	
Switched beam	Electrical
Adaptive array	Electrical

of the transmitter increasing the signal-to-noise ratio (SNR) of the receivers. This larger SNR can be exploited for energy savings, higher throughput or simpler systems among others.

After a basic beamforming discussion in section II, the problems of current solutions in the different application domains are analysed (section III). This results in several architecture implications. A system design is presented in section IV, followed by the processing architecture in section V. The amount of processing and the trade-off between central processing and hierarchical processing are discussed and different methods of beamforming are mapped on the architecture.

A. *Related work*

The array antenna was already proposed and implemented in the beginning of the last century. Mechanically steered array and phased array antennas were used for radar during WWII. Electronically steered phased array systems are used since the 1950s. [3] Recently there has been increasing interest as part of MIMO systems for 3G, 4G, WLAN etc. These systems use multiple antennas in order to exploit space diversity, multi-path diversity, beamforming (directivity), spatial filtering or space-time coding. [5].

Research is being performed on optical beamforming in relation to astronomy by [6]. The ESA research project NATALIA is aiming at designing a small phased array satellite receiver, but more focussed on the antenna design [7]. In the area of processing architectures for beamforming applications, there is the MONARCH processor [8] designed by Raytheon and sponsored by DARPA, which focusses on maximum achievable processing power, or the TRIPS architecture [9] as an example of a dataflow-machine.

II. PHASED ARRAY BEAMFORMING

In this section we will provide a basic outline of the principle of beamforming and some relevant characteristics. Next some options for the main operating principle are discussed.

A. *Principle*

Beamforming is based on the principle of interference. Interference is the pattern resulting from the addition of two or more (usually correlated) waves. For in-phase signals, the waves add up constructively and for out-of-phase signals the waves add up destructively. Assume a single omni-directional wave source, emitting a spherical waveform $x(t) = A\cos(2\pi f t + \theta)$, with A the amplitude, f the frequency, t time and θ the initial phase. At a large distance, in the far field region, the wavefront of this source arrives almost at the same time at two relatively closely placed receivers (antennas) with their plane perpendicular to the direction of the source. Thus, if we neglect this small arrival time error, the wavefront arriving at the receivers can be seen as planar and the two signals add up constructively. We call the two or more antennas in a plane, the array.

However, if the plane of the array is not perpendicular to the direction of the source, but under a certain angle, the wavefront arrives at different times at the antennas. If the antennas are placed a distance d apart and the wavefront arrives at an angle ϑ incident to the array (DOA), the wavefront travels a distance $d \cdot \sin(\vartheta)$ further to the next antenna. Depending on the frequency of the wave, this time delay results in a phase delay ($\Delta\theta = \omega \cdot \Delta t$). This shown in figure 1.

The maximum signal amplitude is received for a wavefront perpendicular to the array, thus if we correct the delay between the antennas for the angle we are interested in, it is as if the wavefront is perpendicular to the array and the maximum signal amplitude is received when a signal is coming from that angle. We can determine the sensitivity of an array with equidistant elements into each direction by calculating the array factor [3], [10], [11]:

$$S_a(\vartheta) = \sum_{i=1}^{K} e^{j\frac{2\pi}{\lambda_0}(K-i)d\sin(\vartheta)} \qquad (1)$$

, with K the number of elements, d the distance between elements, λ_0 the wavelength in free space and

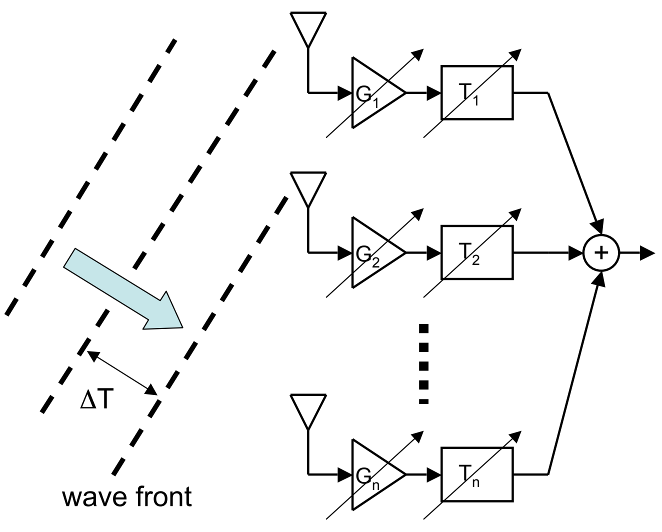


Fig. 1. Phased array antenna with adjustable gain and time delay corrections

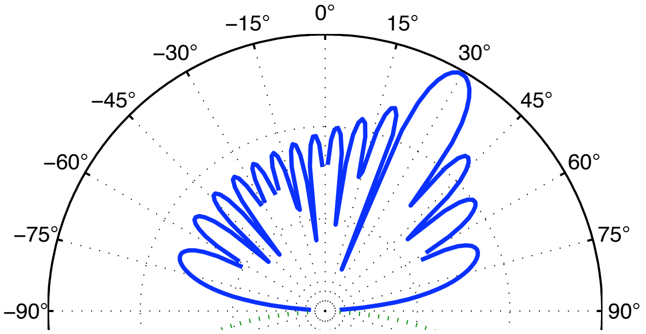


Fig. 2. Polar plot of the phased array angular sensitivity

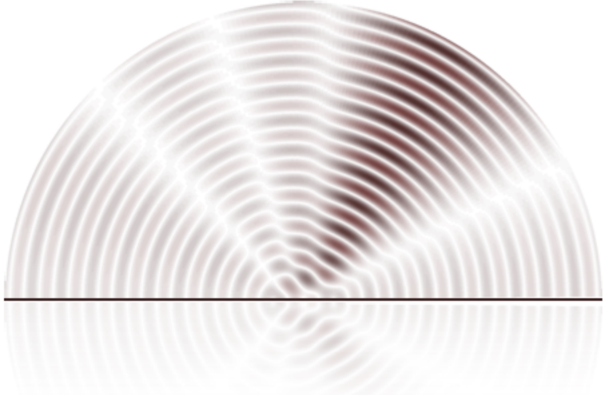


Fig. 3. Contrast representing power radiation pattern

ϑ the DOA. The result is shown in figure 2 and in an alternative form in figure 3. Besides the array factor, the sensitivity or gain of each antenna element itself can also be dependent on the angle (DOA). This element factor will combine with the array factor to give the final sensitivity in each direction ($S = S_e \cdot S_a$ [3]). An isotropic antenna is equally sensitive in all directions and is assumed for the remainder of this paper.

Beamsteering determines the gain and delay for each antenna to create a certain angular sensitivity or radiation pattern. For example to direct the main beam in the intended direction or to attenuate an interfering signal. Many advanced algorithms exist to determine the beamsteering parameters [10], [11], which are outside the scope of this project.

B. Characteristics

From the discussion of the previous section, we can deduce a number of characteristics of phased array systems.

- If we increase the array size (by increasing K or d), the beam-width of the main beam decreases, which results in a higher angular resolution.
- If we achieve a higher precision time or phase delay for each antenna, we achieve a higher angular (ϑ) precision.
- For a higher SNR, we can achieve a higher (dynamic) range, a higher throughput or a higher energy efficiency.
- For a higher sampling (measurement) rate, we achieve a better time resolution, which can be used for a higher distance resolution and/or a larger channel bandwidth, for example.

C. Delay correction

An array without correction is most sensitive perpendicular to the plane of the array. By correcting for the delay from a certain direction, the array is most sensitive in that direction. As the angle increases, the area of the wavefront that reaches an antenna becomes less. A smaller (effective) area results in a wider main beam. As mentioned, the delay of each antenna must be corrected for. The distance of the antenna results in a time delay, but for a certain frequency this results in a phase delay.

C.1 Time delay

The time delay between antennas can be corrected for by using different path lengths between the antennas and the location where the signals are added. For beamsteering, these different path lengths must be changeable. If digital processing is used, one can think of adjusting the sample moment of each ADC. A different option is by using buffers, which is a time delay implemented digitally. Also, if the needed sample time is in between two samples, interpolation can be exploited to estimate the signal amplitude.

The time delay corrects the difference between the planar wavefront from a certain angle and the signals at the array completely. Therefore it is not dependent on the actual signal and any signal with any bandwidth can be used (of course limited by the rest of the system). For this reason this solution is often called a true time delay (TTD).

C.2 Phase delay

As the phase is dependent on the frequency and time, a time delay results in a phase delay (PD) for a fixed frequency. However, the amount of phase delay is thus also dependent on the frequency. If we correct the delay by implementing a phase delay, the delay is only approximately constant around the intended frequency (see section IV-B). This results in a solution which is only suitable for signal with a small bandwidth compared to the carrier frequency.

A phase delay can be implemented by a filter. This filter can be in the analog domain or the digital domain. In the digital domain a FIR filter can be used, which consists of complex multiplications followed by addition. A FIR filter corresponds to performing a truncated convolution. For a simple phase shift a single complex multiplication for each antenna can be used.

Another option, which can be seen as performing a number of parallel convolutions or filters is the FFT. The window used for the FFT determines the shape that the signal is convolved with. Without a window (which means a rectangular window), this filter shape is a sinc function. The advantage of an FFT is that the sensitivity of the main beams in each direction is calculated in one operation. The number of directions corresponds to the maximum number of non-overlapping main beams, which corresponds to the number of antennas and thus FFT bins used. In order to differentiate between performing an FFT on the received signal after beamforming, for example for OFDM reasons, we will refer to this method of using a spatial FFT. Both digital options work on complex signal, which means a Hilbert transform must be performed first.[12]

III. Requirements

During the introduction an overview is given of the advantages of using phased array beamforming. Beamforming can be beneficial for any radio (RF) system, such as broadcasting (DVB), radar, (radio) astronomy, mobile communications (3G/4G) or wireless communications (WLAN/WiMax), because the spectrum is scarce. We would like our beamforming architecture to be as generic as possible. Therefore we will analyse the requirements and problems of three application domains: satellite reception, radar and mobile and wireless communications.

A. Applications

Satellite reception is normally achieved by using a dish antenna. The DVB-S [13] standard specifies an RF frequency of 10.7 to 12.75 GHz, a maximum SNR of 16 dB, a channel bandwidth up to 33 MHz and satellites are at least 5° apart. The satellite position in europe is from about 20° to 50° elevation and $5°E$ to $30°E$ azimuth. The disadvantages of satellite dishes are that they must be aimed mechanically and the dish must be at a fixed position (stationary). It is also quite large. This makes the dish unsuitable for moving (or often relocating) vehicles. A phased array system can therefore be beneficial. For flexibility we would like to be able to form two or three independent beams.

Radar is a specialised application aimed at detecting and locating reflecting objects or targets. It is for example used for scanning and tracking or guiding objects. The characteristics mentioned in section II-B determine the possible performance and often maximum performance is required. Therefore, future phased array radar systems require a large array size (a few thousand), a high SNR (100dB) and a high sample rate (100MHz). We will look at radar systems using 7 to 13 GHz signals. We would like to be able to track or scan tens of objects, thus that many independent beams. Phased array radar has been used since the 1950s [3]. Recent systems use separate antennas and front-end produced in specialised processes, making the antenna front-ends costly because of the relatively low volumes. Furthermore, a large amount of specifically designed central processing is used. This makes the system not easily scalable nor power efficient. [11]

Mobile communications uses a single omni-directional antenna for handhelds and a few antennas which are made directional by construction at the base station. Two antennas in each direction are used for diversity reasons. For wireless communications, a number of new standards use MIMO and thus optionally beamforming with a few (2 or 3) antennas. These designs have the advantage of being commercial products for a large volume market, which also implies that cost is important. Only recently some designs have appeared that support multiple standards, but most are designed for a (large volume) specific application. Therefore, the designs do not exploit more than a few antennas, are not flexible for multiple standards and are not scalable for different applications. Most wireless and mobile communications operate from around 2 to 5 GHz, up to 5 MHz bandwidth and up to 90 dB SNR. A few (up to four) independent beams would be a good start. [5]

B. Implications & goals

The goal of this project is to design a cheap generic flexible efficient array transceiver platform. This allows for one converging solution for telecom, military and consumer products, which can support multiple standards and is adaptable to future standards. Resulting from the requirements and limitations of section III we get the following implications:

- For functionality, size and cost reasons, we would like an highly integrated design suitable for high volume production.
- In order to support multiple standards, we would like a software defined radio based platform.
- A flexible, efficient and adaptable software defined radio platform needs reconfigurable hardware.
- A platform suitable for a large variety of applications and required performance must be easily scalable.
- For cost, complexity and scalability reasons a hierarchical design with largely identical components is preferred.

The approach taken is to integrate the analog front-end and the digital reconfigurable processing on a (single) CMOS chip. These antenna and processing elements (tiles) are then combined on multiple hierarchical levels (MPSoC, chips on a board, boards in a cabinet).

IV. System design

The received (RF) signal is at a high carrier frequency up to 13GHz, which must be down-converted to an intermediate frequency (IF) for further processing. This is done by mixing the RF signal with a local oscillator (LO) signal. [12] Beamforming can be performed at several stages in this design. Also at each stage a time or phase delay can be performed in multiple domains. We will also show that the delay can be corrected after down-conversion. For each beam we would like to form at the same time, we need a parallel time or phase delay element per antenna or we need to time share if possible. An advantage of beamforming in the digital domain is that extra time or phase delays simply means extra processing and no other hardware. We can also support multiple methods of beamforming and easily switch between them.

A. Front-end

If the beamforming is performed at RF, optical elements can be used to electronically change the path length of the signal after the antenna. This has the advantage that it implements a TTD so it is suitable for wide-band signals. The disadvantage is that it is not easily integrated on CMOS or easy to design for completely flexible beamsteering. Also the SNR is limited and I/O is difficult. For these reasons it is not considered in our research. Another option is an analog filter as phase delay, which is difficult to design at these high frequencies, needing an (active) filter with high Q and SNR. On the other hand there are no synchronisation problems between antennas as we can simply set the needed phase delay for each. Digital filters at RF are not an option as ADCs are not yet feasible; they are either limited by the frequency or by the SNR. [12]

A phase delay of the signal of interest can also be implemented by setting the initial phase of the LO for each antenna. The disadvantage is that the timing and distribution of each LO is critical and difficult to implement. On the other hand, if beamforming is performed after down-conversion, this timing and distribution is critical anyway, because for correct beamforming, the timing of all LOs must be synchronous or known and corrected for.

Beamforming can also be performed at IF, after down-conversion. As said, the timing and distribution is a problem, but if this is solved delay correction is easier. Analog phase delay operate at a much lower frequency than at RF, but on the other hand, they need to be wide-band. More importantly, ADCs and digital beamforming can be employed. This easily allows for multiple methods of delay correction and multiple beams. One can for example use an TTD implementation for the main direction of interest, an FFT as a fan-of-beams for scanning and multiple beams by complex multiplication phase shifts for tracking.

Because of the timing and distribution problem most current phased array systems use RF beamforming. We will, however, further assume the use of an IF with digital beamforming because of the discussed advantages.

B. Delay at baseband

For a 10 GHz signal, $\lambda \approx 30$ mm and if the antennas are at a distance $d = \frac{\lambda}{2}$, which is the maximum distance before grating lobes occur [3], [11], they are 15 mm apart. The phase difference between two adjacent antennas is between 0 and π for 0° to 90° DOA. For a large array the phase difference between the two outer antennas can thus become quite large relative to the frequency. At IF we have:

$$
\begin{aligned}
x(t) &= A\cos(\omega t + \varphi) \\
x_{RF}(t)x_{LO}(t) &= \frac{A_{RF}A_{LO}}{2} \\
&\quad \Big[\cos\Big((\omega_{RF}+\omega_{LO})t + (\varphi_{RF}+\varphi_{LO})\Big) \\
&\quad + \cos\Big((\omega_{RF}-\omega_{LO})t + (\varphi_{RF}-\varphi_{LO})\Big)\Big]
\end{aligned}
\tag{2}
$$

For a time delay Δt and a frequency around RF ($\omega = \omega_{RF} + \Delta\omega$), we have:

$$\begin{aligned} x_{RF}(t) &= \cos\Big((\omega_{RF} + \Delta\omega)(t + \Delta t) + \varphi_{RF}\Big) \\ &= \cos(\omega_{RF}t + \Delta\omega t + \omega_{RF}\Delta t + \Delta\omega\Delta t + \varphi_{RF}) \\ x_{IF}(t) &= x_{RF}(t)x_{LO}(t) \\ &= \Big[\cos\Big((\omega_{RF} + \Delta\omega - \omega_{LO})t \\ &\qquad + (\omega_{RF} + \Delta\omega)\Delta t + (\varphi_{RF} - \varphi_{LO})\Big) + \dots\Big] \\ &= [\cos\Big((\omega_{RF} - \omega_{LO})t + (\varphi_{RF} - \varphi_{LO}) + \Delta\omega t \\ &\qquad + \omega_{RF}\Delta t + \Delta\omega\Delta t\Big) + \dots] \end{aligned} \tag{3}$$

where $\cos((\omega_{RF} - \omega_{LO})t + (\varphi_{RF} - \varphi_{LO}) + \Delta\omega t$ is the wanted signal, while $\omega_{RF}\Delta t + \Delta\omega\Delta t$ is negated by a time delay correction, but only $\omega_{RF}\Delta t$ for a phase delay correction.

From the above we can make two observations: the time delay is the same at IF as at RF, which means it results in a relatively small phase shift compared to the IF. Furthermore, phase delay correction leaves an error term of $\Delta\omega\Delta t$, which becomes larger for larger $\Delta\omega$, i.e. further from the RF. Thus the phase delay solutions is only suitable for signals with a small bandwidth compared to the RF ($\approx< 10\%$).

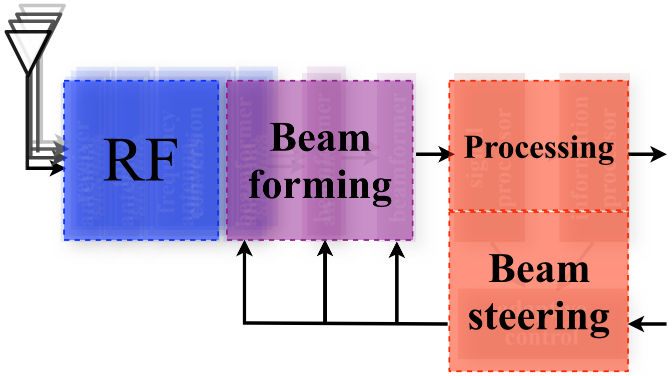


Fig. 4. Main system blocks

C. *Blocks*

A basic phased array system consist of an RF front-end, beamforming, further (application dependent) signal processing and beamsteering. This is shown in figure 4. Besides the basics we need calibration and equalisation to correct for distortions of the front-end, either mechanical or electrical. This must be done for each antenna before beamforming, as the distortion for each antenna can be different and can not be separated after beamforming. Note that this calibration/equalisation consists of a gain and phase correction for each antenna. These parameters can therefore possibly be combined with the parameters of the PD beamforming. An alternative is correcting in the analog domain as part of the front-end itself.

Thus, taking an IF front-end with digital beamforming, the remainder of the system design consists of beamforming and beamsteering. For the beamforming we already discussed the three options: TTD beamforming, complex multiplications or FFT beamforming. Note that we can combine the TTD option with the PD options. It is for example possible to "pre-steer" the array into the main direction of interest and use the PD options to calculate a number of different beams. For the PD options a Hilbert filter is needed to create a complex representation of the signal. In case of an FFT, a window can be applied to adjust the main beam characteristics and/or time domain behaviour (for a complex multiplication the response is determined by its multiplication values in the same way) [12]. Beamforming can also be performed hierarchical, i.e. in multiple stages.

Beamsteering consists of signal processing and information processing feedback and adaptive control. Signal processing takes care of processing the actual signal content, which is of course dependent on the application. For example, selecting a satellite channel or determining the range of a target for radar. Information processing uses the information of the signal or a user to determine the next step. For example, selecting between different modes of operation. Information from the signal and information processing as well as directions from the user are used to determine the parameters needed for beamsteering.

Together this results in the high-level system design shown in figure 5.

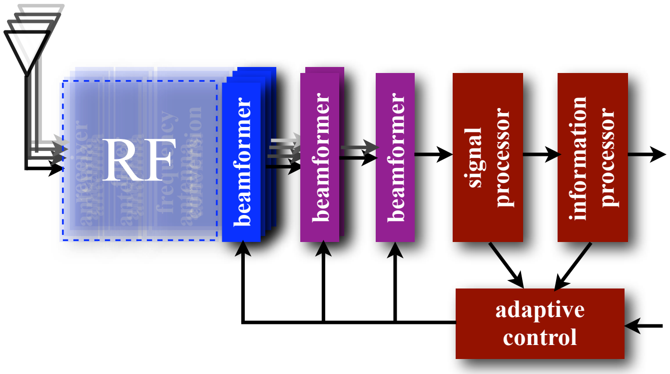


Fig. 5. High-level system design

V. Processing architecture

The processing architecture must support beamforming, for which we discussed three methods, and beamsteering. As a consequence it must also cope with combining the information of all the antennas. Our main focus is on beamforming and I/O.

A. Processing

We will first discuss the advantages and disadvantages of each beamforming method, including its computational complexity.

A.1 Beamforming methods

The true time delay has the advantage that it corrects the exact difference between the wave front from a certain direction and the signals received at the antennas. Therefore it is suitable for wide-band signals. To implement the TTD we need to be able to delay and adjust the amount of delay of each antenna. For this we can use a buffer. However, the amount of delay is small compared to the sample time. For example, for a 10 GHz signal, the delay between antennas is in the range of pico- to nano-seconds. For an ADC at 100MHz sample rate, the time between two samples is in the nano-second range. Thus, oversampling is needed, which is not practical at these high sample rates with an acceptable SNR (see section III) or we need to estimate the values between samples. A simple form of estimation (first-order) is interpolation. To implement interpolation we need 2 multiplications and 1 subtraction or 1 multiplication and an addition and subtraction per antenna. Furthermore for combining the signals for beamforming we need an addition per antenna. Thus we have 4 operations per antenna per beam.

The phase delay options work with complex signals. To create a complex representation of the signal we can perform a Hilbert transform. This Hilbert transform can be implemented in the analog domain or the digital domain. As a complex signal is represented with two real signals, the analog solution has the disadvantage of needing twice as many ADCs. Furthermore, a Hilbert transform can be implemented (approximated) by duplicating the signal and adding a 90° phase shift in one of the signal paths, which is difficult to design for wide-band signals or by a quadrature mixer, which makes the LO distribution even more difficult as each antenna also needs an extra 90° phase shifted LO signal. The Hilbert transform can also be performed in the digital domain by implementing a Hilbert filter which approximates the Hilbert transform. How well the approximation must be is determined by the application requirement on the signal and determines the needed processing. For a FIR filter implementation we need about half the number of multiply-accumelate (MAC) operations as filter taps, because half of the coefficients are zero. As this is for each antenna, the amount of processing can easily become as large as the beamforming itself, however, it only needs to be performed once when multiple beams are calculated. [12]

The phase delay correction with a complex multiplication has the advantage that it is flexible with respect to the beam-shape and the angle (DOA). Each beam is independent and can have a different shape (and direction). However, for each extra beam we need the same amount of extra processing. For each antenna we need a complex multiplication (which consists of 4 multiplications, an addition and a subtraction) and a complex addition (which consists of two additions) to combine antennas. Thus we have 8 operations per antenna per beam.

The FFT calculates as many beams as antennas at once. However, each beam is equally spaced and of the same shape. This regularity makes it possible for the FFT to compute more efficient than the same number of beams with complex multiplications. The angle and filter shape can be set for one beam by using a window before the FFT, but this adds processing. All the other beams have the same shape and are at a fixed angle with respect to the set beam. The FFT is well suited for scanning, as the beams are so positioned next to each other, slightly overlapping as to cover all the angles. The amount of processing for calculating all beams at once is $\frac{1}{2}N \log_2 N$ butterfly operations for power-of-two N, with N the number of antennas. A butterfly operation consists of four multiplications and three additions and subtractions.

A.2 Data rate

Beamforming can be characterised as a streaming application as data is continuously coming in and processed. The data rate and thus processing requirements are high. For radar applications, we have a 100 MHz sample rate with 16-bit samples ($\approx$ 100 dB). For 1024 antennas, the FFT beamforming would need $100 \cdot 10^6 \cdot 5120 \cdot 10 \approx 5T$ 16-bit operations per second (ops). For sattelite applications with 16x16 antennas, three beams and 66 MHz sample rate with 4-bit samples ($\approx$ 20 dB), we would need $66 \cdot 10^6 \cdot 8 \cdot 256 \cdot 3 \approx 400G$ 4-bit ops. Both without the needed Hilbert filter.

Fortunately, the processing for each method is similar and regular, thus we can use a regular dataflow architecture. On the other hand, the I/O rate is high, which is problematic because I/O in radar applications is expensive, difficult to design and vulnerable. Thus, we would like to limit the data rate as soon as possible, by combining the data from antennas (beamforming) as soon as possible. But the combined data can not be separated later, thus we loose flexibility, and the distributed processing must be synchronised.

B. Architecture

So far we found that beamforming is a high datarate streaming application. Furthermore we would like to integrate the analogue RF-frontend with digital reconfigurable processing on a single chip as a tile and combine processing tiles on multiple hierarchical levels. We would like a processing architecture which can support all three options of beamforming. Also, it is preferable to limit I/O as soon as possible.

First we will discuss central versus hierarchical processing and explain the need for reconfigurability. Finally, we will show how to map beamforming on a regular tiled processing array.

B.1 Central versus hierarchical

Central processing gives the most flexibility as all the data is available unprocessed. This makes a central processing architecture easy to adapt, either in functionality or operation. Another advantage is that it is easy to design because one needs not to split the beamforming into parts and determine the dependabilities. On the other hand, there is a single point of failure which leads to a lower MTBF. Of course redundancy can be applied, but this is costly if everything is duplicated and it is still vulnerable if only parts are duplicated. Other disadvantages are that the large amount of data from the antennas must be routed to the central location, thus there is a lot of I/O.

Hierarchical processing limits the data and thus the I/O as soon as possible. This requires the processing to be distributed, which brings another advantage; the architecture becomes scalable. When antennas are added, processing is also automatically added and can relatively easy be integrated in the system. Furthermore, if one of the processing elements breaks down, the remainders stay operational. Thus, we have graceful degradation instead of all-or-nothing when the central processing breaks down. Of course this comes at the cost of less flexibility as combined data can not be separated later in the processing chain.

B.2 Reconfigurability

The solution we would like to propose is to regain flexibility of the hierarchical distributed processing approach by making the system reconfigurable. A reconfigurable hierarchical processing array has a number of advantages. We can configure the system to use only part of the phased array or create multiple sub-arrays. In this way we can save energy (at the cost of less gain and a larger beam-width or grating lobes), or use only the number of antennas needed to increase the lifetime of the array. Also, we can use the array for multiple functions at the same time, for example part transmitting and part transceiving.

Broken tiles can be avoided. The system can be configured to make optimum use of the remaining tiles. Therefore the phased array stays useful even if some of the elements have broken down. Note that for this to work the I/O routing must also be flexible.

Reconfigurability inherently comes down to having an adaptable system, to adapt to changing environments, while maintaining the quality of service. New wireless and DVB standards also require this adaptability to make optimum use of the current conditions.

B.3 Mapping

As set out above, a generic scalable tile-based hierarchical reconfigurable processing array has many compelling advantages. This leads to an architecture as shown in figure 6. Next, we will look at how to map the three beamforming methods on this architecture.

First we would like to mention that combining the antennas can be performed in a tree-like way with the antennas as leaves, or in a chain with the next antenna added to the result of the previous antennas. The advantage of the latter is greater flexibility in connecting

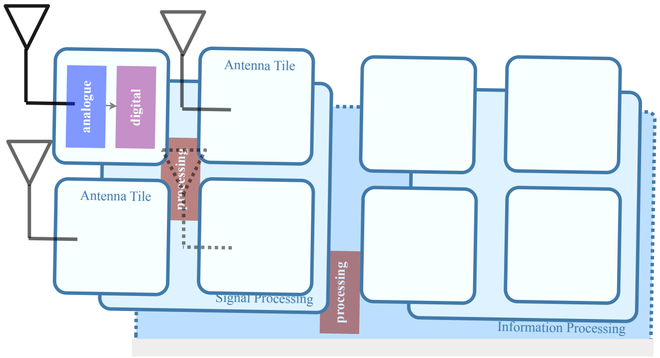
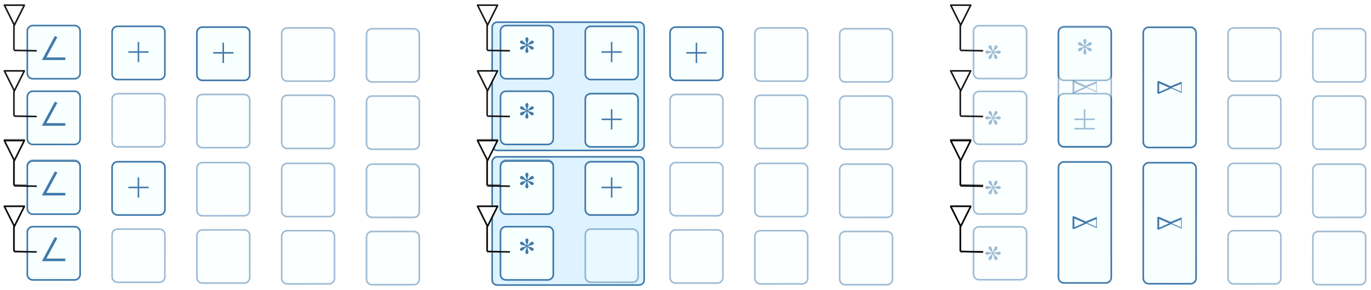


Fig. 6. Integrated generic scalable tile-based hierarchical reconfigurable architecture



(a) TTD (b) Complex multiplication (c) FFT

Fig. 7. Mapping of the three beamforming methods on a regular processing array

the antennas and better scalability, but the disadvantage is that buffers are needed. A combination is also possible. We will focus on tree-like combining.

If we assume that a tile can perform a complex multiplication or addition, this is enough processing for each tile to calculate one (interpolated) time-delayed value. Thus the time-delayed version of each antenna can be calculated assuming enough buffering is available. This buffer, however, is not trivial and can add quite an amount of hardware to the design. Next the antennas are added in a tree-like fashion as shown in figure 7a. Note, that in this case, the data is always transfered to the next column. Adding antennas include the needed processing for interpolation and leaves some processing for combining, making the approach easily scalable.

The complex multiplication of one antenna can obviously be mapped on the first tile. If four tiles are grouped on the next hierarchical level, we can map the last addition on the free tile of the group and chain these together for the final result as shown in figure 7b. Again, two processing tiles per antenna are enough to be easily scalable.

For an FFT, the first column can be used for windowing. Next, the butterfly is mapped. This operation does not fit on a single tile. We can map the complex multiplication on one tile and the remaining two additions and subtractions on the second tile. For each doubling of the number of antennas, the FFT needs another stage and thus another processing column. This can be implemented as another hierarchical level, making this approach a little less scalable. This mapping is shown in figure 7c.

VI. Conclusion

In this paper we have shown the rationale for choosing an integrated generic scalable reconfigurable tile-based hierarchical phased array platform. A high-level system design was presented and a preliminary mapping has been shown for the proposed processing architecture. Beamforming is a data-driven streaming process which lends itself well for a regular scalable architecture. Beamsteering on the other hand is much more control-oriented and future work will focus on how to support beamsteering on the proposed architecture as well. Besides beamsteering many open questions are presented to be addressed.

References

[1] B. Nauta, E. A. M. Klumperink, A. B. J. Kokkeler, and G. J. M. Smit. CMOS Beamforming Techniques. Project proposal, University of Twente, 2006.

[2] H. Schurer, G.J.M. Smit, A.B.J. Kokkeler, K.C. Rovers, and M.D. van der Burgwal. NEST (NEtherlands STreaming) - Reconfigureerbare digitale antenne processing. Project proposal, University of Twente, 2007.

[3] Hubregt J Visser. *Array and phased array antenna basics.* Wiley, Chichester, 2005.

[4] Lal Chand Godara. *Smart antennas.* CRC Press, Boca Raton, Fla, 2004.

[5] Arya Behzad. Radio design for mimo systems with an emphasis on ieee 802.11n. *ISSCC*, 2007. Tutorial.

[6] Telecommunication Engineering University of Twente. Broadband photonic beamformer. http://www.el.utwente.nl/te/research/BPBF/BPBF.htm.

[7] European Space Agency ESA Telecommunications. NATALIA: New Automotive Tracking Antenna for Low-cost Innovative Applications. http://telecom.esa.int/telecom/www/object/index.cfm?fobjectid=27952.

[8] Michael et al. Vahey. MONARCH: A First Generation Polymorphic Computing Processor. 2006.

[9] TRIPS. Tera-op, reliable, intelligently adaptive processing system. http://www.cs.utexas.edu/users/cart/trips/.

[10] Harry L Van, Trees. *Optimum array processing*, volume Detection, estimation and modulation theory. Wiley-Interscience, New York, 2002.

[11] Merrill I. Skolnik. *Introduction to radar systems.* McGraw Hill, Boston, 2001.

[12] K.C. Rovers. Front-end research for a low-cost spectrum analyser. Master's thesis, University of Twente, June 2006.

[13] ETSI European Telecommunications Standards Institute. Digital Video Broadcasting (DVB); DVB-S & DVB-S2 specifications. http://www.etsi.org/.