Microprocessors and Microsystems 35 (2011) 716–728

Contents lists available at SciVerse ScienceDirect

Microprocessors and Microsystems

journal homepage: www.elsevier.com/locate/micpro

Mobile satellite reception with a virtual satellite dish based on a reconfigurable multi-processor architecture ☆

M.D. van de Burgwal [a,*], K.C. Rovers [a], K.C.H. Blom [a], A.B.J. Kokkeler [a], G.J.M. Smit [a]

[a] Computer Architectures for Embedded Systems Group, Faculty of Electrical Engineering, Math and Computer Science, University of Twente Enschede, The Netherlands

ARTICLE INFO

Article history:
Available online 12 September 2011

Keywords:
Adaptive beamforming
Phased array
Virtual satellite dish
Reconfigurable processor
Montium TP
MPSoC

ABSTRACT

Traditionally, mechanically steered dishes or analog phased array beamforming systems have been used for radio frequency receivers, where strong directivity and high performance were much more important than low-cost requirements. Real-time controlled digital phased array beamforming could not be realized due to the high computational requirements and the implementation costs. Today, digital hardware has become powerful enough to perform the massive number of operations required for real-time digital beamforming. With the continuously decreasing price per transistor, high performance signal processing has become available by using multi-processor architectures. More and more applications are using beamforming to improve the spatial utilization of communication channels, resulting in many dedicated digital architectures for specific applications. By using a reconfigurable architecture, a single hardware platform can be used for different applications with different processing needs.

In this article, we show how a reconfigurable multi-processor system-on-chip based architecture can be used for phased array processing, including an advanced tracking mechanism to continuously receive signals with a mobile satellite receiver. An adaptive beamformer for DVB-S satellite reception is presented that uses an Extended Constant Modulus Algorithm to track satellites. The receiver consists of 8 antennas and is mapped on three reconfigurable Montium TP processors. With a scenario based on a phased array antenna mounted on the roof of a car, we show that the adaptive steering algorithm is robust in dynamic scenarios and correctly demodulates the received signal.

1. Introduction

Satellite reception requires accurate pointing of the receiving antenna. For home installations, this can be done relatively easy with a dish antenna that is mounted to a fixed plane like a wall or roof. In mobile situations, there is no fixed plane to mount the dish on, hence a complex actuator mechanism is required to continuously point a dish antenna towards the transmitter. A solution is to use an electronically steerable antenna, referred to as a 'virtual satellite dish'. To control such an antenna, advanced Digital Signal Processing (DSP) algorithms are required to compensate for the movement of the antenna and optimize the quality of the received signal. Typically, these algorithms require a vast amount of processing power and should be executed quickly to keep the receiver pointed at the transmitter.

Phased array beamforming techniques have been used in radar systems for many years already. The design of these systems is mainly driven by functional requirements (e.g., resolution, sensitivity, response time) where non-functional requirements (e.g., costs, power consumption) are of secondary concern [1]. For that reason, no low-cost, low-power phased array systems are available yet. However, in areas like Software Defined Radio (SDR) and satellite receivers, phased array antennas show great promise but their large scale introduction has been obstructed by the high costs involved. Our goal is to develop a low-cost, low-power phased array receiver platform. This can be realized by using a scalable architecture that is flexible enough to support multiple applications, such that the same architecture can be reused. Reconfigurable Multi-Processor System-on-Chip (MPSoC) based architectures seem to be promising, as they offer high performance (by enabling parallel processing through multiple processors) and are flexible within a certain application domain (reconfiguration enables efficient reuse of hardware by reconfiguring parts of the hardware or the application). Conventional phased array receivers typically use a large amount of dedicated central processing hardware, making the system neither scalable nor power efficient [2]. This article presents the implementation of an adaptive beam steering algorithm onto a reconfigurable multi-processor based architecture. We show

☆ This research is done within the projects CMOS Beamforming Techniques (07620) and NEST (10346), supported by the Dutch Technology Foundation STW, applied science division of NWO and the Technology Program of the Ministry of Economic Affairs.

* Corresponding author. Tel.: +31 53 4894178.

E-mail addresses: m.d.vandeburgwal@utwente.nl (M.D. van de Burgwal), k.c.rovers@utwente.nl (K.C. Rovers), k.c.h.blom@utwente.nl (K.C.H. Blom), a.b.j.kokkeler@utwente.nl (A.B.J. Kokkeler), g.j.m.smit@utwente.nl (G.J.M. Smit).

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doi:10.1016/j.micpro.2011.08.005

how such an architecture can be utilized for efficient execution of beamforming, adaptive beam steering and symbol demodulation.

After an introduction to phased array systems and their different applications in Section 2, we will provide a more thorough discussion on the required processing and its complexity in Section 3. The target reconfigurable multi-processor architecture is introduced in Section 4 and the mapping of the processing blocks onto the reconfigurable processors in this platform is presented in Section 5. Finally, the scheduling of the entire application on the multi-processor architecture is discussed in Section 6, together with an example operation of the application to demonstrate the performance.

2. Mobile satellite signal reception

Digital television broadcasts are transmitted by many different satellites in different frequency ranges. The most commonly used range is the K_u band (11.7–12.7 GHz in The Americas and Australia and 10.7–12.75 GHz in Europe) where most systems use Digital Video Broadcast for Satellite (DVB-S) for transmission [3]. The DVB-S standard specifies a channel bandwidth of 36 MHz (effective bandwidth used is 50 MHz due to pulse shaping filter roll-off), transmitted within the 10.7–12.75 GHz frequency range. The modulation technique used for individual DVB-S channels is Quadrature Phase Shift Keying (QPSK). QPSK uses four different phases to represent transmitted information, equally distributed on the unit circle of the IQ plane. Each of these four phases represents a symbol, which is represented by two data bits. Since the transmission of two subsequent symbols requires instantaneous phase shifts in the transmitted output signal, high frequency components are introduced. A pulse shaping filter is used to decrease the effects these phase shifts by spreading the signal into a slightly larger frequency band such that the high frequency components are attenuated. For correct demodulation, QPSK requires a minimum Signal to Noise Ratio (SNR) at the receiver of 16 dB.

2.1. Conventional satellite dish

Conventionally, DVB-S receivers use a parabolic dish antenna. Such an antenna can be constructed easily and has a high efficiency. A parabolic dish antenna focuses a wavefront incoming from a single direction to one focal point. By mounting a Low Noise Block (LNB) at the focal point, the Radio Frequency (RF) signal is captured, amplified, downconverted to an Intermediate Frequency (IF) and transmitted to the remote modem that applies channel selection and demodulation of the IF signal. This construction requires the parabolic dish antenna to be tightly aligned with the transmitter, otherwise the wavefront is not efficiently focused and the LNB cannot successfully capture the transmitted signal.

A dish antenna could be used for reception of DVB-S signals in mobile environments (for example, in a moving car or on a yacht), but mechanical control is required to continuously steer the dish. Moreover, since a dish antenna would cause considerable air resistance when mounted on a car, it is not an efficient solution for mobile satellite reception. Hybrid solutions are commercially available, where the dish is reduced to multiple waveguide antennas which are mechanically steered [4]. Such systems can be embedded in a relatively compact housing, but still rely on mechanical parts (which are sensitive to wear and possibly consume much energy).

2.2. Virtual satellite dish

The virtual satellite dish discussed in this article is based on a phased array antenna. Such an antenna is fully steered electronically, which means it does not rely on mechanical control. An advantage of such an antenna is the possibility of receiving broadcasts from multiple satellites simultaneously, by applying DSP techniques. This is useful, when multiple users want to receive signals from different satellites simultaneously.

Phased array systems are based on the principle of interference using multiple antennas in an array to make a transceiver directional (see Fig. 1). Interference is the pattern resulting from the addition of two or more (partly) 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 s in time and space:

$$s(t, l) = A \cdot \cos(\omega t \pm kl) \quad (1)$$

with A the amplitude, ω the frequency, k the wave number, t time and l the path length from the source. For a source in the far field perpendicular to the array, the wavefront is considered planar and the received signals add up constructively. From other directions, the wavefront arrives at different times at the antennas. Typically, the antennas are placed a distance $d = \lambda/2$ apart (where λ is the wavelength of the received signal). If the wavefront arrives at an angle θ incident to the array, the wavefront travels a distance $\Delta l = d \cdot \sin(\theta)$ further to the next antenna, which results in a time delay:

$$\Delta t = \frac{\Delta l}{c} = \frac{d \cdot \sin(\theta)}{c} \quad (2)$$

where c is the propagation speed of radio waves. If the signal is a narrowband signal, this time delay can be considered as a phase shift:

$$\Delta\psi = \omega \cdot \Delta t \quad (3)$$

hence by applying the inverse phase shift, the time delay is corrected. Therefore, such an antenna array is usually referred to as 'phased array antenna'.

By correcting the phase, the direction of maximum sensitivity is steered [1]. After the RF front end for each antenna, sampled signals are combined by the beamforming processing to create a resulting signal with for example a maximum sensitivity in a direction of interest or a minimum sensitivity (a *null*) in the direction of an interfering signal. Beam steering refers to changing the shape and direction of the formed beam by changing the gain and phase of complex multiplier stages, such that a certain angular sensitivity is created.

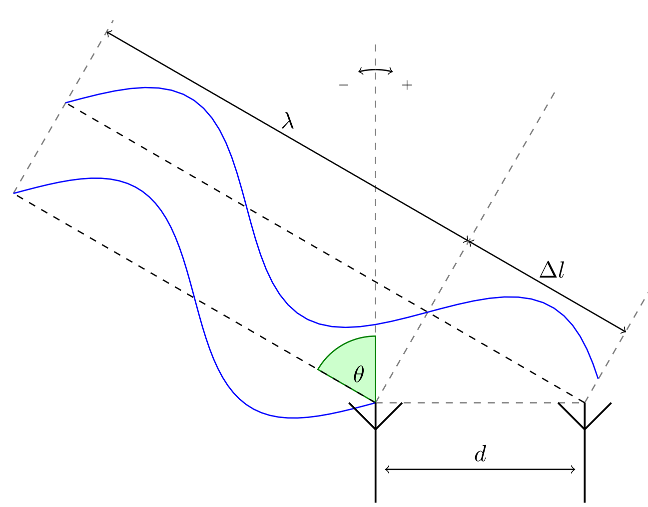

Fig. 1. Wavefront received by multiple antennas in a phased array.