On The

Softer Side

Software Defined Radio

Adaptive Beam Forming Techniques in Software

Beam forming can meet the challenges of increasing spectral efficiency and improving wireless communications system performance by significantly increasing the reception and transmission ranges and reducing the probability of interception of secure transmissions.

Liana Land, Field Applications Engineer
Spectrum Signal Processing (USA) Inc.

Beam forming is a technique that utilizes an array of sensor elements to focus a receiver channel on a specific signal of interest (SOI) or to transmit a signal in a specific direction. Historically, it has been at the heart of radar and sonar signal processing. Radar beam-forming techniques are used for target detection in the presence of ground clutter and jamming signals. Physical constraints must also be overcome, such as the required length of the antenna to achieve the desired beam width and spatial resolution. Sonar processing has additional constraints that can make signal reception and, therefore, beam forming even more challenging. For example, the irregular properties of the ocean environment limit the possible resolution of sonar systems.

Many signals intelligence and other wireless communication applications can benefit from beam-forming techniques. A beam-forming approach is regarded as a vital solution to the challenge of increasing spectral efficiency and improving wireless communications system performance. The benefits include allowing for an increased capacity of a communications network through the use of Space Division Multiple Access (SDMA) techniques. Since a beam former can steer the look direction toward the SOI, this frees the carrier frequency for use by other resources. Secondly, because the beam former is focused in a particular direction, the antenna sensitivity can be increased for a better signal-to-noise ratio (SNR), a factor that is especially important when receiving weak signals. Both reception and transmission ranges can be significantly increased with beam forming. Additionally, beam-forming techniques provide reduced probability of interception of secure transmissions. Finally, signal interference is reduced due to the ability to reject interfering signals.

Beam Forming Background

Beam forming is a form of spatial filtering used to distinguish the spatial properties between a SOI and the noise and interfering signals. Beam-forming principles apply to both the transmission and reception of signals, but discussion here will be limited to the receive systems.

Beam forming is accomplished through the use of an array of sensors such as antenna, hydrophones, and so on. In order to proceed with the discussion of beam forming, it is important to note some basic assumptions. First, a signal originating far away from the sensor array can be modeled as a plane wave. Next, the signal received by each sensor element is a time-delayed (phase-shifted) version of the signal received by the other sensor elements. Finally, an N-element beam-forming system is capable of forming up to N beams. Figure 1 illustrates a basic beam-forming system.

In early beam-forming systems, known as delay-and-sum beam formers, the output of each sensor was delayed to allow the coherent addition of all the inputs. The result was maximization of the power of the SOI.

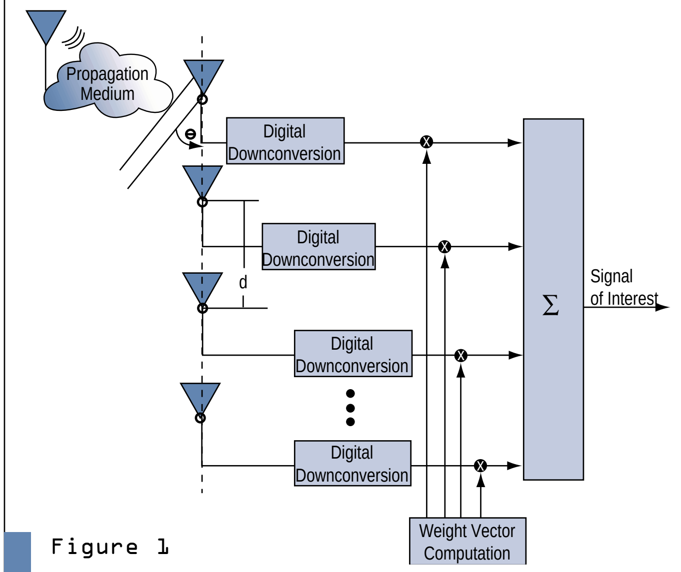


Figure 1

Basic beam-forming system.

While the delay-and-sum beam formers succeeded in maximizing the SOI, they provided no means of reducing noise or canceling intentional and unintentional interfering signals. The neces-sity for improvements in system performance brought about methods for adaptive beam forming. Adaptive beam formers continually update the value of the weights applied to each of the input signals to allow for real-time adjustment of the system's look direction, the angle location of the SOI. Adaptive beam formers have the additional capability to steer nulls in the direction of interfering signals. An adaptive beam former comprised of N sensor elements can effectively reject N-1 interfering signals.

Figure 2 illustrates the theoretical spatial response of a four-element beam former. Nulls in antenna response are steered for rejecting signals at -45 degrees, -10 degrees and +60 degrees. The main lobe is formed toward the SOI located at +30 degrees. Note that the look direction is not centered at +30 degrees due to the system optimization for the rejection of interfering signals.

The algorithm used to calculate the weighting vector for an adaptive beam former must be carefully chosen. Two commonly used algorithms are Least Mean Squares (LMS) and Recursive Least Squares (RLS). Trade-offs between the rate of convergence and the complexity of the implementation of the algorithm must be considered. The LMS algorithm is relatively simple to design yet has slow convergence time. The LMS algorithm can be a good choice for systems with a relatively small number of sensor elements. The RLS algorithm is reasonably complex, but converges rapidly. Therefore, the RLS algorithm is better suited to systems with large sensor arrays.

A summary of the RLS method is shown in Figure 3 (see "Advanced Signal Processing Handbook," by Stergios Stergiopulos). The RLS algorithm recursion is initialized by choosing a starting value for the inverse weight-error correlation matrix, P(n) that insures the nonsingularity of the matrix. The weights vector, w(0), is set to zero. Subsequently, for every input sample, the gain, k(n), and error signal, α(n), are computed. The updated weighting vector is calculated by incrementing the previous value by the complex conjugate of the priori estimated error multiplied by the time-varying gain vector. It is important to note that the RLS algorithm does not require any matrix inversion computations, which would significantly increase the processing time, as the inverse weight-error correlation matrix is computed directly.

Beam Former Implementation

When implementing a beam former, one of the first exercises in mapping the application to a hardware platform is the calculation of the required processing resources. When designing a beam-forming system, the required processing can be estimated as the number (N) of sensor complex dot products per beam, where a complex dot product requires eight oper-

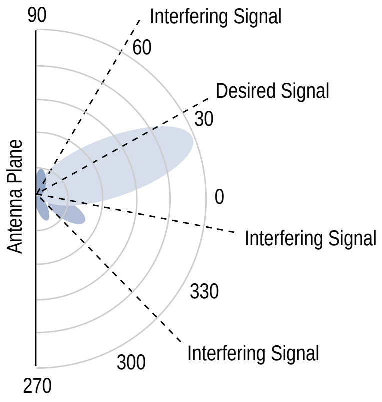
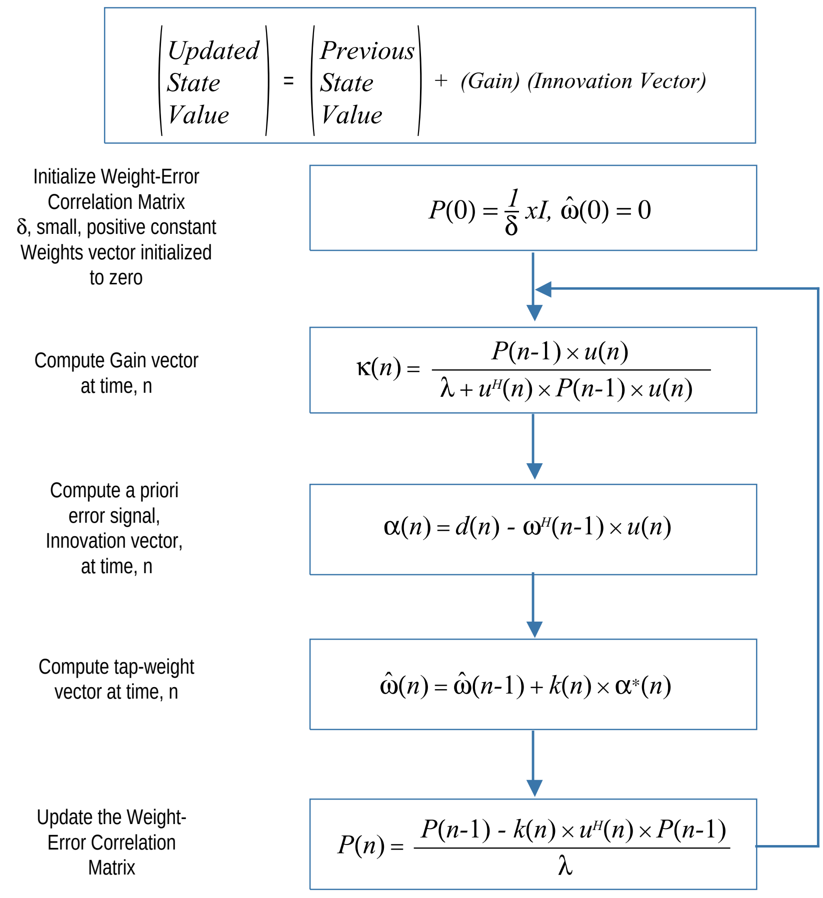


Figure 2

Spatial response of four-element beam former.



Where the weighting factor is: $0 << \lambda \leq 1$,used to minimize affect of samples in distant past

u(n) = tap-input vector at time, n

d(n) = desired response at time, n

Figure 3

The Recursive Least Squares method for adaptive beam forming.

ations per sample. Therefore: $NumFLOPs = 8*M*N*f_s$, where M is the number of beams, and f_s is the sampling frequency.

Sonar applications typically have low (acoustic range) sampling rates and a large number of sensor inputs. Radar, signals intelligence and wireless communication applications tend to have much higher sampling rates to allow for higher bandwidth signals. A typical G4 PowerPC processor operates at 450-500 MHz. For example, a signals intelligence application with eight antenna elements, six desired beams and a sampling rate of 80 MSPS would require at least 60 processors. There are numerous 6U VME and cPCI boards available, each with four G4 PowerPC processors. In a 20-slot chassis (reserving one slot for a system controller) this provides a maximum of 80 processors, enough to handle the example application.

However, with this large number of processors the data flow management can become as complex as the beam-forming application itself. Each beam-forming processing element must have access to the I and Q data—the real and imaginary components of a complex signal—from each sensor input corresponding to the beam in formation. Not only is it necessary to move large amounts of data throughout the system for processing, it must be done deterministically to ensure meaningful results. Embedded fabrics such as RapidIO are ideal for such data movement. So, in the example above, the overhead associated with the distribution of the data throughout the system and inter-processor communication must also be taken into consideration. The overhead can easily be > 50% of the required processing.

A common method of dealing with high bandwidth data from the A/D converters is to perform digital downconversion (DDC) and filtering to reduce the desired bandwidth around the frequency of interest to baseband I and Q components. DDCs are commonly implemented with discrete components such as the Texas Instruments GC4016. However, a more flexible implementation is through the use of FPGAs. These offer hundreds of MACs (Multiply Accumulates) per device and, therefore, are well suited to performing such high bandwidth, arithmetically intense and repetitive computations. For

Using Adaptive Beam Forming in Real-Life Tactical Situations

Manuel Uhm, Sr. Manager, Strategic Marketing
Lee Pucker, CTO, Spectrum Signal Processing

Military command, control and computer communications often consist of multiple ad-hoc tactical networks that interface to each other, as well as backbone communications networks connected through a variety of wireless communications gateways. Within this “system of systems”, the military currently supports hundreds of legacy waveforms—each with its own unique air interface specification and independent link/network layer protocols. At any given time, the specific waveforms required by warfighters operating in this communications environment are dependent upon both the situational environment and the availability of the various tactical, strategic and coalition communications networks.

To address these new requirements, military communications technologies are beginning to transition from single function “stove pipe” devices to software defined radio (SDR) architectures that can be dynamically reconfigured to meet mission requirements by using programmable devices in lieu of ASICs. These programmable devices allow each channel within the radio to be dynamically reconfigured “on-the-fly” with disparate waveforms, both at the time of deployment and during operation. Thus, each radio is able to dynamically support both legacy waveforms for voice and low-speed data, and new wideband waveforms with sufficient bandwidth for multimedia data and video conferencing.

When adaptive beam forming is incorporated into SDR, this paradigm extends directly to the beam forming subsystem. Fundamental to the use of adaptive beam forming in a dynamic waveform environment is the ability to modify the algorithms used in calculating the weighting vector in the beam-forming subsystem. This provides an optimized algorithm for each supported waveform. By utilizing programmable devices in the calculation of the weighting vector, a new weighting algorithm can be loaded each time a waveform is changed.

Figure

Illustrating how beam forming could be used in a battlefield situation. With a soldier behind enemy lines, imagery that contains critical positional information is relayed from a satellite and an Airborne Warning and Control System (AWACS) aircraft via an ad hoc network. The use of beam forming ensures the enemy tanks cannot intercept the lines of communication to the soldier and also enables the extended range required by the tank to communicate with the High Mobility Multipurpose Wheeled Vehicle (HMMWV).

In this manner, all tactical and strategic SDRs can use beam forming when communicating to each other or sending messages to legacy radios. Beam forming would be advantageous for:

- Reduced probability of intercept: the more precisely one can focus the beam the less likely an enemy could be in the communications path and intercept the signal.
- Extended range: focusing the energy of the transmitter enables the reception of signals that may be beyond the range of a comparable omni-directional antenna.
- Increased signal-to-noise ratio (SNR): by canceling out interfering signals, the SNR can be dramatically improved.

As a result, adaptive beam forming is becoming increasingly integrated into high-performance software defined radios.

example, the Virtex-II FPGA using a core supplied by Xilinx can process submicrosecond 1024 point FFTs. With the implementation of a DDC, it is only necessary to process the bandwidth of interest. For the example above, f_s becomes, say 2 MHz, requiring only an estimated two G4s to form the six beams. Using FPGAs for the first processing stage provides benefits, such as speed of hardware processing, while maintaining the flexibility of software implementations.

For baseband processing applications, the Motorola PowerPC G4 processor performs well. The G4 is a 32-bit processor that supports double-precision floating-point operation. A great advantage of the PowerPC over traditional DSPs is the support for robust real-time operating systems such as VxWorks and RTLinux. Also, there are optimized Vector Signal Image Processing Library (VSIPL) packages available for the G4 processing platform, reducing development efforts by negating the need for assembly coded math operations. This abstraction from the hardware facilitates code portability and future reuse.

This combination of FPGAs and PowerPCs means that the entire beam-forming application can be implemented through a combination of C/C++ and Hardware Description Language (HDL), which is readily ported to new platforms, combating obsolescence and providing future upgrade paths.

The SDR-3000 from Spectrum Signal Processing is an example of a COTS platform that meets the rigorous requirements for beam forming. The SDR-3000 tightly couples multiple FPGAs and PowerPCs via a Serial RapidIO-based fabric. The combination of high-performance general-purpose processing devices with a high-performance embedded fabric results in a coherent system suitable for beam forming. ❚❚

Spectrum Signal Processing (USA)
Columbia, MD.
(410) 872-0202.
[www.spectrumsignal.com].

Motorola Semiconductor Group
Austin, TX.
(512) 895-2000.
[www.motorola.com].

RapidIO Trade Association
Austin, TX.
(512) 305-0070.
[www.rapidio.org].

Texas Instruments
Dallas, TX.
(800) 336-5236.
[www.ti.com].

Xilinx
San Jose, CA.
(408) 559-7778.
[www.xilinx.com].