Phased Array Receive and Transmit Tiles
with Integrated Analog Beamformer

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1. Introduction

This white paper describes a method for constructing a low cost phased array antenna using array tiles. For a given aperture area, electronically steered phased arrays cost much more than passive antennas such as parabolic reflectors. High performance phased arrays, particularly military radars, use transmit/receive (T/R) modules for each array element. Phased arrays for communications and other applications are constructed in a contiguous manner with a single radio frequency (RF) circuit board to process the signals from all array elements. The array tile approach hybridizes aspects of the T/R module and the single contiguous array design. The modular approach enables high quantity manufacturing of array tiles for multiple products, rather than a custom RF backplane design for each product. Since a T/R module is required for each array element, the overall antenna cost is high. The array tile is essentially a T/R module for four or more antenna elements, and provides the optimal compromise between modularity and integration.

Each tile consists of an aperture with multiple array elements, an RF board that feeds the elements using an integrated analog beamformer chip, and connectors for RF inputs and outputs, DC power, and control lines. The primary applications are phased array antennas for broadcasting satellite service (BSS), direct broadcast satellite (DBS), and very small aperture terminals (VSAT). Communications, radar, and other applications are also possible.

2. Tile Configurations

The tiles may be configured for:

1. Receive
2. Transmit
3. Receive/transmit (shared aperture)

Phased arrays can be designed for either a horizon to horizon (“full-sky”) field of view or a limited field of view. The choice is primarily dictated by the expected angular range of the source of interest relative to the phased array antenna. The advantage of a full-sky array is a wider range of angles of arrival for which the source signal can be acquired. The advantage of a limited field of view array is that a higher antenna gain can be realized for a given number of elements. The field of view of an array is determined by the radiation pattern of the elements in the array and by the decrease in antenna gain ("scan loss") as the beam is steered. For the DBS and BSS applications, in-motion arrays require tiles with a full-sky field of view, or a limited field of view array with a rough-pointing mechanical platform that maintains the antenna orientation so that the source of interest remains within the field of view of the array. Examples of limited array fields of view include the sky arc occupied by satellites in geostationary orbit (GSO) as viewed from a given range of latitudes and an omnidirectional pattern over a limited range of elevation angles for a phased array antenna on a rotating, horizontal platform.

It is possible to hybridize an array so that it includes a combination of limited field of view elements and full-sky or omnidirectional elements. This would be useful for an antenna designed to receive signals from both GSO satellites and nonstationary low earth orbit (LEO) or medium earth orbit (MEO) satellites.

Phased arrays can scan in one or two dimensions. A 1D scanning array can steer a beam over a one-dimensional arc in the sky. A 2D array steers a beam over a solid angular region. 2D arrays offer greater flexibility but require more elements than a 1D array. For fixed array applications with satellites in geostationary orbit, a 1D array can be implemented to steer the antenna beam along the GSO arc to point at a desired satellite.

Shared aperture tiles can be used to combine transmit and receive functions in one phased array antenna. Multiple frequency bands can also be combined using the shared aperture approach. Dual or multiband elements can be used to achieve this, or antennas for a lower frequency band can be interspersed between more densely packed higher band elements. An example of a dual frequency array is a combined Ku and Ka band system.

3. Polarization and Number of Elements Per Tile

This discussion assumes that one beamformer chip consists of two four element beamformers. These polarization configurations can be modified for tiles having beamformer chips with a different number of inputs (receive) or outputs (transmit). In order to increase the level of system integration, it is also possible to use multiple beamformer chips per tile and thereby increase the number of antenna elements per tile.

For a beamformer chip with two four element beamformers, the array tile can be constructed in three possible configurations:

1. Eight single polarization antenna elements. The tile has one RF output corresponding to the polarization of the antenna elements (linear or circular).
2. Four dual-polarized antenna elements. The tile has two RF outputs for two orthogonal polarizations (horizontal/vertical linear or right hand/left hand circular), allowing electronics after the phased array antenna to select the final polarization. This is a dual polarized phased array. An antenna for satellite applications with two orthogonal polarization outputs is commonly referred to as universal polarization.

3. Four dual-polarized antenna elements with electronically selected or rotated polarization. The tile has one RF output and includes additional electronics before or after the beamformer chip to select one of two orthogonal polarizations or to rotate the polarization of the tile.

4. Receive Array Tile Functional Description

The major components of each array tile are the antenna elements, optionally discrete low noise amplifiers, an integrated analog beamformer, and RF, control, and DC power input/output lines.

Antenna Elements

The antenna elements are designed such that the phased array has a given field of view. For a phased array with full sky field of view, the antenna elements are electrically small and spaced nominally one half the wavelength at the high end of the operating bandwidth. For an array with limited field of view, the elements are electrically larger and are custom designed for the designed field of view. Limited field of view elements may be realized using corporate fed, passive phased arrays or other antenna types that realize a given field of view.

Low Noise Amplifiers

For high sensitivity applications such as DBS and VSAT antennas, discrete low noise amplifiers (LNAs) may be required to amplify the antenna element output signals before the beamformer electronics. To minimize system noise introduced by transmission line and interconnect losses, the LNAs should be located as close as possible to the antenna elements. Radio frequency connector cables or PCB traces connect the antenna elements to the LNA inputs and the LNA outputs to the beamformer inputs. The LNAs could also be attached directly to the terminals of the antenna elements to reduce connector losses.

Integrated Analog Beamformer

The major cost driver for a phased array antenna is the beamformer electronics. To minimize the cost of this component of the system, the beamformer can be integrated onto a single chip. Further cost reduction can be obtained by integrating the beamformer electronics for multiple array elements on one chip. The beamformer chip functionality may include low noise amplifiers, phase shifters, variable gain amplifiers, and a combiner. The simplest architecture required for phase-only beam steering consists of phase shifters and a combiner, but the other components can be included to increase the utility of the beamformer as needed. Amplitude control allows more precise control of the antenna beam pattern, including reduction of sidelobes to reduce ground noise and meet regulatory pattern mask requirements. Both digital and analog beamforming could be employed. For broadband consumer applications, analog beamforming is used to enable broadband processing at the lowest possible cost. The beamformer combines signals from the antenna elements on the tile to produce an RF output corresponding to a steered beam, with each RF input signal shifted in phase and amplitude according to phase and gain control signals.

For applications such as multi-user terminals, it is desirable to form multiple simultaneous beams. This can be done by splitting the element outputs after the LNAs and routing the signal to the inputs of multiple beamformer chips. Each beamformer chip forms a separate, independently steerable beam.

RF Inputs/Outputs, DC and Digital Control Lines

The receive array tile requires one RF output per polarization. DC input connectors for the tile provide power to the beamformer chip, LNA, and other electronics. Digital input lines provide control signals to select the amplitude and phase states used by the beamformer chip to create an electronically steered antenna beam. A beamformer control unit with embedded digital signal processing hardware generates the digital amplitude and phase control signals that are distributed to the phased array tiles. It is also possible to integrate the beamformer control unit on the beamformer chip using a mixed-signal analog and digital architecture.

5. Transmit Array Tile Functional Description

The major components of a transmit array tile are the antenna elements, optionally discrete power amplifiers amplifiers, an integrated analog beamformer, and RF, control, and DC power input/output lines.

Antenna Elements

Considerations for transmit antenna elements are similar to that described above for the receive array.

Power Amplifiers

To provide adequate radiated power, the signal level arriving at the input to the array tile must be amplified to an appropriate power level. Power amplifiers can be integrated on the beamformer chip, or discrete power amplifiers can be used for applications with power requirements that are too great for integrated RF electronics. For full-sky arrays with many elements, sufficient total power can be achieved using the on-chip power amplifiers. For limited field of view arrays or high-power uplinks, on-chip amplifiers may not generate sufficient power, so off-chip power amplifiers are located between the beamformer and the antenna elements.

Integrated Analog Beamformer

For a transmit array tile, the beamformer has one RF input per polarization, which is split into separate signal paths with individually controllable phase shifters and possibly variable gain amplifiers. After phase shifting, gain control, and amplification, the RF outputs are each connected to array elements. Additional electronics, including power amplification and other functions, may be located between the RF outputs and the array elements.

RF Inputs/Outputs, DC and Digital Control Lines

The digital control lines and DC power are similar to the receive array, except that more power is typically required for the power amplifiers in the transmit array. One RF signal input is required per polarization.

6. Phased Array Assembly

The tiles have mechanical attachment fixtures that allow tiles to be snapped together conveniently during manufacture of a phased array. The attachment fixtures may be alignment pins, guides, or flanges. The attachment fixtures are designed to be low cost but maintain accurate relative positioning between antenna elements on adjacent array tiles. The assembled array should be sufficiently stable to survive high winds, vibration and acceleration on a mobile platform, and other sources of mechanical shocks.

The tile RF signal lines, DC power, and digital control lines are connected to the array power supply and beamformer control unit with individual connectors on the back or side of the tile. The connectors can either mate with flexible cables or fixed connectors on a large PCB backplane. Alternately, the connectors can be located on the side of the tiles, so that adjacent tiles are joined electrically as well as mechanically. For the receive array, each tile in this case includes an RF input which is added in a combiner to the signal produced by the tile and output to a connector that is daisy chained to the next tile. Care must be taken so that RF signals are properly combined to maintain equal phase lengths from a master connector on one center tile for the entire array, a center tile for each row in the array, or a supporting RF backplane.

Various shapes are possible for the array tile. For a rectangular tile, attachment fixtures are located on the four sides of the tile, allowing the tiles to be connected in a two dimensional grid pattern to form a large phased array. A hexagonal array allows a reduced number of elements for a given aperture size as compared to a rectangular array. The tile shape required for a hexagonal array is nonrectangular, and consists of the union of several equilateral triangles. The number of the equilateral triangles is chosen so that the number of elements matches the number of RF ports on the beamformer chip. One possible tile shape for a hexagonal array is a parallelogram with two rows of four elements and one row of four elements offset by half the element spacing. For array antenna applications requiring only steering in one dimension, the tiles can be designed to connect only on two sides, so they can be chained to form a linear (one dimensional) phased array.

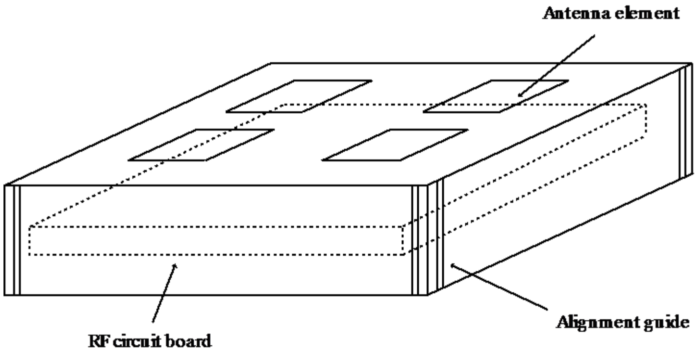

Figure 1. Phased array tile.

Shared Aperture Array Tiles

For some applications, it is desirable to minimize the total size and weight of a phased array. In this case, a shared-aperture tile is needed. A shared aperture tile contains both transmit and receive RF signal handling. Using a duplexer circuit, the antenna elements on the array can be shared by the transmitter and receiver, or separate elements for the transmit and receive sides can be interleaved on the array.

7. Test and Evaluation

An advantage of the array tile approach is that the electrical, thermal, and mechanical performance of the tile can undergo test and evaluation before assembly of the full array. Array phase and amplitude calibration can also be performed at this stage. The RF circuit board can include adjustable phase delays to allow fine-scale correction of the relative element phases, to simplify calibration of the full array. An automated test fixture is attached to the RF, DC, and digital control line connectors. If additional test points are required, a dedicated test connector can be included.

8. 16 x 2 Element Ku Band Dual Circular Polarization Receive Array Tile

This section describes a particular realization of the phased array tile concept for a Ku band satellite downlink phased array antenna. The largest segment of direct broadcast satellite and very small aperture terminal data services is Ku band (10-15 GHz). Services within this band use both linear and circular polarizations. Since linear polarization on a mobile platform requires electronic polarization control, but circular polarization does not, in this respect circular polarization is easier to implement. The tile design in this section is a dual right and left hand circularly polarized Ku band receiving phased array tile for the broadcasting satellite service (BSS) and direct broadcast satellite (DBS) markets. The band allocated to this service in the U.S. is 12.2 to 12.7 GHz. The array tile is designed for a “full-sky” field of view with nearly horizon-to-horizon beam steering range.

The array tile has 16 dual-polarized antenna elements in a 4 x 4 array and one RF beam output per polarization. There are 16 right hand circular polarized antenna element feed ports and 16 left hand circular polarized antenna element feed ports, so the tile is a 16 x 2 element array, where 16 is the number of dual-polarized elements with two feed ports each and the total number of feed ports is 32. The beamformer electronics forms one steerable beam for right hand circular polarization and a second independently steerable beam for left hand circular polarization. The array tile consists of four blocks of four dual-polarized elements each with one beamformer chip per block, for a total of four beamformer chips. For each block of four elements, one of the four element beamformers on the chip forms a right hand circular polarized beam, and the other four element beamformer forms a left hand circular polarized beam.

The antenna elements are low loss patch antennas with two feed lines and a 180 degree hybrid to achieve two antenna ports, one that radiates RHC polarization and the other that radiates LHC polarization. Other realizations of a dual-polarization antenna element can also be used. The element shape and dimensions are designed using standard antenna optimization procedures to realize a given antenna impedance at the antenna ports. Considered as a complete structure, the array element and hybrid comprise a two-port antenna with one port feeding LHC polarization and the other RHC polarization. For a full-sky array, the elements are one half wavelength in each linear dimension. The wavelength in the 12.2 to 12.7 GHz band is 2.4 cm. The array grid spacing, or the offset between element center points, is one half wavelength (2.4 cm). The 16 element array is a square of side 9.6 cm.

The antenna ports feed a low noise amplifier (LNA) consisting of a transistor amplifier with associated bias control circuitry. The amplifier is designed using standard techniques to have a very low noise figure. The antenna is active impedance matched to the amplifiers, so that the active impedances presented by the array to the amplifiers as the beam is steered remain close to the optimal noise impedance expected by the LNAs. Active impedance matching is accomplished using antenna software design optimization software. Precise values for the antenna geometry are dictated by the active impedance matching condition. The noise figure of the beamformer chip is 4 dB, which means that the gain of the LNA must be 20 dB in order to limit the noise contribution of the beamformer chip to 4 K. To minimize noise due to electrical loss, the LNAs are located directly at the element feed terminals on an RF printed circuit board. Traces on the printed circuit board (PCB) feed the LNA outputs to the RF inputs of a beamformer chip.

The outputs of the beamformer chips are added in two groups of four with two 4 to 1 power combiners implemented to form two beam outputs for the tile, one for each polarization. The combiners are implemented as passive components on the printed circuit board (PCB). The power combiner and transmission line connections are routed so that the phase length of each signal path is identical. This ensures that when all phase shifters in the beamformer chips are commanded to the zero phase state, the beam formed by the tile is steered to the broadside direction.

The tile external interface consists of two RF outputs, two DC power supply inputs, signal and power grounds, and digital control lines. Each beamformer chip requires 12 digital control lines to control the phase and gain settings of the RF beamformer signal paths and two clock inputs, one for each of the two four input beamformers on the chip. To reduce the number of external connections, a serial to parallel converter is included on the PCB to convert a single digital input line into the 12 digital control and clock signals. The DC, power ground, and digital lines use a standard low-frequency connector. The RF outputs are connected using two high frequency connectors to maintain signal integrity and minimize losses. Each RF output connector has a signal ground shield.

8.1 Design Alternatives

An alternative design employs RF switches at each element to switch between the RHC and LHC output ports, so that instead of dual polarization outputs, the array polarization is selectable between RHC and LHC polarization. The advantage of this design is that the number of beamformer chips required is reduced from four to two. The polarization can also be factory-selectable and fixed in operational use.

The tile can also be designed with a different number of elements. To achieve a greater economy of scale, at the cost of reduced flexibility and possibly lower manufacturing yield, the number of elements per tile could be increased. The number of element ports should be evenly divisible by the number of inputs or outputs on the beamformer chips, to avoid unused beamformer channels. A power of two is preferred because the power combiners can be designed for an even power of two inputs, but other numbers of elements can also be accomodated. The array also need not be square, so that the elements can be arranged into a grid of M rows of elements and N columns, for a total of MN elements. A four element tile is also possible, with one beamformer chip.

9. 16 x 2 Element Ku Band Linear Polarization Agile Receive Array Tile

For many satellite broadcast services, the polarization of the transmitted fields is linear. In order for the phased array to achieve maximum signal quality when mounted on a mobile platform for in-motion applications, the array must be polarization-agile and have the capability to track the transponder polarization adaptively. The tile operates in the 12.2 to 12.7 GHz BSS and DBS band.

For the polarization agile receive array tile, the antenna elements are horizontal, broadband thickened crossed dipoles over low loss dielectric and ground plane. The dipole elements are nominally one half wavelength in length at the design center frequency of 12.45 GHz. At this frequency, the wavelength is 2.41cm, which means that the length of each dipole is approximately 1.2 cm. The dipole elements are spaced one quarter wavelength above the ground plane, or 0.6 cm. Each dipole consists of two metal arms with a feed transition to a waveguide support. The metal arms and waveguide support are designed using standard antenna optimization procedures to realize a given antenna impedance at the waveguide output port. The waveguide is a transmission line for the received signal and feeds a low noise amplifier (LNA) consisting of a low noise transistor amplifier with associated bias control circuitry. The antenna is active impedance matched to the amplifiers, so that the active impedances presented by the array to the amplifiers as the beam is steered remain close to the optimal noise impedance expected by the LNAs. Active impedance matching is accomplished using antenna software design optimization software. Precise values for the dipole arm shape, feed gap distance and height above ground plane are dictated by the active impedance matching condition.

The array tile has 32 antenna elements in a 4 x 4 array and one RF beam output. The elements are crossed, so that 16 are oriented in one direction and the other 16 are oriented in the orthogonal direction. By combining the outputs of pairs of crossed dipole elements with zero relative phase shift, an arbitrary linear polarization can be synthesized.

The antenna ports feed a low noise amplifier (LNA) consisting of a low noise transistor amplifier with associated bias control circuitry. To minimize noise due to electrical loss, the LNAs are located directly at the element feed terminals on an RF printed circuit board. Traces on the printed circuit board (PCB) feed the LNA outputs to the RF inputs of a beamformer chip.

For each group of four crossed dipoles, the output ports of four dipoles with a like orientation are fed after amplification by an LNA to four inputs of one half of a dual four channel beamformer chip. The output ports of the other four dipoles with orthogonal orientation are fed to the other four inputs of the second half of the dual four channel beamformer chip. The PCB includes four total beamformer chips, each connected to a group of four crossed dipoles in the same manner. The beam outputs for each beamformer block are added with an 8 to 1 power combiner to form a single beam output for the tile.

The power combiner and transmission line connections are routed so that the phase length of each signal path is identical. This ensures that when all phase shifters in the beamformer chips are commanded to the zero phase state, the beam formed by the tile is steered to the broadside direction.

The tile external interface consists of one RF output, two DC power supply inputs, signal and power grounds, and digital control lines. Each beamformer chip requires 12 digital control lines to control the phase and gain settings of the RF beamformer signal paths and two clock inputs, one for each of the two four input beamformers on the chip. To reduce the number of external connections, a serial to parallel converter is included on the PCB to convert a single digital input line into the 12 digital control and clock signals. The DC, power ground, and digital lines use a standard low-frequency connector. The RF output is connected using a high frequency connector to maintain signal integrity and minimize losses and includes a signal ground shield.

9.1 Design Alternatives

The array tile design described above includes an 8 to 1 power combiner. The combiner could be replaced by analog to digital converters, so that after each group of four element port outputs are combined as analog signals, at the next level the beamforming is accomplished using digital signal processing. For a given bandwidth, digital processing is more costly than analog, but offers greater flexibility. Analog subtiles with digital processing to combine tile outputs provides a compromise between cost and flexibility.