# Performance of Smart Antennas with FPGA Signal Processors over 3G Antennas

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**Abstract**— Demands for increased capacity and better quality of service are driving the development of new wireless technologies such as "smart" antenna arrays. The FPGAs operate as powerful digital signal processing devices, which can meet the requirements of adaptive antenna arrays. The smart antenna systems are efficient than the existing 3G antenna systems as they can track the location of a mobile user and also increase channel capacity through spatial diversity. FPGAs offer greater flexibility for performing functions such as acquisition control, digital down-conversion, demodulation and matched filtering. This paper discuses in creating beam-forming smart antennas using FPGA's as well as the ways in which smart antennas will overcome the performance of 3G antennas.

**Index Terms**— Smart Antenna, FPGA, Adaptive antenna arrays, spatial diversity, 3G antenna, beam forming, Direction of arrival, MIMO Systems .

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## 1 INTRODUCTION

THE name smart refers to the signal processing capability that forms vital part of the adaptive antenna system which controls the antenna pattern by updating a set of antenna weights. A smart antenna is a digital wireless communications antenna system that takes advantage of diversity effect at the source (transmitter), the destination (receiver), or both. Smart antenna for mobile communication has received enormous interests World wide in recent years. In the last decade wireless cellular communication has experienced rapid growth in the demand for provision of new wireless multimedia services such as Internet access, multimedia data transfer and video conferencing. Smart antennas are also known as adaptive array antennas, multiple antennas and recently MIMO. They are antenna arrays with smart signal processing algorithms that are used to identify spatial signal signature such as the direction of arrival (DOA) of the signal, and use it to calculate beam forming vectors, to track and locate the antenna beam on the mobile/target. A smart antenna has the potential to reduce noise, to increase signal to noise ratio and enhance system capacity. Several approaches have been studied to introduce smart antenna technology into GSM, IS-136 and third generation systems. Recently, they have been applied to mobile stations or handsets.

Smart antennas involve processing of signal induced on an array of antennas. They have application in the areas of radar, sonar, medical imaging location based application and communications. Smart antennas have the property of spatial Filtering, this makes it possible to receive energy from a particular direction while simultaneously blocking it from another direction. Unlike ASICs, field-programmable gated arrays (FPGAs) are reconfigurable, that is, their internal structure is only partially fixed at fabrication, leaving to the application designer the wiring of the internal logic for the intended task. This can significantly shorten design and production, for FPGA-based embedded systems. FPGAs are especially well suited for embedded systems (e.g., cellular system base station line cards, or mobile stations) because, beside an area of reconfigurable logical elements, they can also incorporate large amounts of memory, high-speed DSP blocks, clock management circuitry, high speed input/output (I/O), as well as support for external memory, and high-speed networking and communications bus standards. The objective of this paper is to investigate FPGA suitability for efficient smart antenna array embedded receivers. In the process, we overview an Altera FPGA-based design environment, and implement conventional and enhanced (BF, MRC, MREC) receiver algorithms. It is demonstrated that FPGA implementations of eigen mode-based combining adapted to the slow variations in channel statistics can yield near-optimum bit error rate (BER) performance, for affordable power budgets [1].

Future broadband wireless communication systems require the development of smart antennas that are small, and affordable to a large number of users. These smart antennas must also go broadband to provide newer generation technology the possibility of offering more capacity to the

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busiest cell sites or create specific beams for each mobile user while continuously adapting to the changing environment. In the 3-G system, the possibility offered by smart antennas will permit to have less interference from other users and will effectively boost the current generation networks.

## 2. PROGRESS OF SMART ANTENNAS

The evolution of smart antennas can be divided into three phases:
Smart antennas are used on uplink only. By using a smart antenna to increase the gain at the base station, both the sensitivity and range are increased. This concept is called high sensitivity receiver (HSR).
In the second phase, directed antenna beams are used on the downlink direction in addition to HSR. In this way, the antenna gain is increased both on uplink and downlink, which implies a spatial filtering in both directions. The method is called spatial filtering for interference reduction (SFIR). In GSM, which is a TDMA/FDMA system this interference reduction results in an increase of the capacity or the quality in the system. In CDMA based systems, due to non-orthogonality between the codes at the receiver, different users will interfere with each other. This is called Multiple Access Interference (MAI) and its effect is reduction of capacity in CDMA network [3].

## 3. BASIC BLOCK OF A SMART ANTENNA SYSTEM

### *Smart* Antenna Receiver

The smart antenna reception part consists of four units. In addition to the antenna itself it contains a radio unit, a beam forming unit and a signal processing unit. The first two structures in figure 1 are used for beamforming in the horizontal plane. Here (a) shows a one–dimensional linear array with uniform element spacing of $\Delta x$. This structure can perform beamforming in azimuth angle within an angular sector, (b) shows a birds eye view of a circular array with angular element spacing of $\Delta\phi = 2\pi/M$. This structure can perform beamforming in all azimuth angles. The last two structures are used for performing two–dimensional beamforming, in both azimuth and elevation angles. (d) Shows a cubic structure with element separations of $\Delta x$, $\Delta y$ and $\Delta z$. The radio unit consists of down–conversion chains and analog-to-digital converters. The signal processing unit will be based on the received signal, calculate the complex weights $w_1 . . . ,w_M$ with which the received signal from each of the array elements is multiplied. These weights will decide the antenna pattern in the uplink direction. The weights can be optimized from two main types of criteria: maximization of received signal from the desired user (e.g. switched beam or phased array) or maximization of the SIR by suppressing the signal from interference sources (adaptive array) [1].

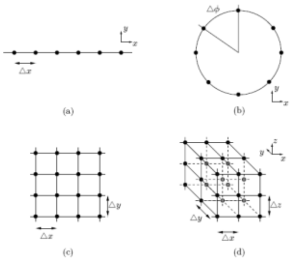

Fig 1: Array geometries of smart antennas

In theory, with M antenna elements one can null out M − 1 interference sources. The method for calculating the weights will differ depending on the type of optimization criterion. When switched beam (SB) is used, the receiver will test all the pre-defined weight vectors and choose the one giving the strongest received signal level. If the phased array approach (PA) is used, which consists of directing a maximum gain beam towards the strongest signal component, the direction-of-arrival is first estimated and then the weights are calculated. If maximization of SIR is to be done, the optimum weight vector $\mathbf{W}_{opt}$ can be computed using a number of algorithms such as optimum combining. Beamforming and signal processing units can normally be integrated into the same unit. [3]

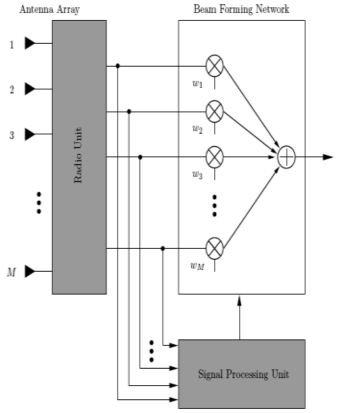

Fig 2: Smart antenna receiver

### Smart Antenna Transmitter

The signal is split into $M$ branches, which are weighted by the complex weights $w_1, . . ,w_M$ in the beam forming unit. The weights decide the radiation patterns in the downlink direction are calculated by the signal processing unit. The radio unit consists of D/A converters and the up converter chains. In a time division duplex system the mobile station and base station use the same carrier frequency only separated in time. In this case the weights calculated on uplink will be optimal on downlink if the channel does not change during the period from uplink to downlink transmission. If frequency division duplex is used, the uplink and downlink are separated in frequency. In this case the optimal weights will generally not be the same because of the channel response dependency on frequency. Thus optimum beamforming on downlink is difficult and the technique most frequently suggested is the geometrical approach of estimating the direction-of-arrival. This direction is used on downlink by choosing the weights $w_1, . . , w_M$. So that the radiation pattern is a lobe or lobes directed towards the desired user which is similar to Phased Array Systems. Due to fading on different signal paths it has been suggested to choose the downlink direction based on averaging the uplink channel over a period of time. This will however be sub-optimum compared to the uplink situation where knowledge about the instantaneous radio channel is available. This means that when the base station on transmission positions zeros in the direction towards other mobile stations than the desired one, it will reduce the interference suffered by these mobiles [2].

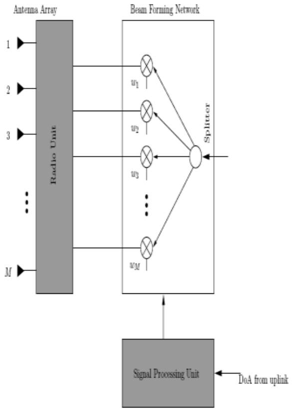

Fig 3: Smart Antenna Transmitter

## 4. FPGA MAKES SMART ANTENNA ARRAYS A REALITY

Smart-antenna technology requires lots of processing bandwidth. Several billion multiply-and-accumulate (MAC) operations take place per second. This exhausts the processing capabilities of many DSPs. To overcome this Some FPGA chips with embedded DSP blocks were introduced. High flexibility is achieved. Provides throughput in excess of 50 GMAC/sec. this also Inherits parallel-processing benefits. Provides throughput that are an order of magnitude greater than the current generation of DSPs [1][2].

A linearly arranged and equally spaced array of antennas forms the basic structure of a beam former. In order to form a beam, each user's information signal is multiplied by a set of complex weights (where the number of weights equals the number of antennas) and then transmitted from the array. The important point in this transmission is that the signals emitted from different antennas in the array differ in phase (which is determined by the distance between antenna elements) as well as amplitude (determined by the weight associated with that antenna).

Changing the direction of the beam, therefore, involves changing the weight set as the spacing between the antenna elements is fixed. The rest of this article describes two such schemes known as switched and adaptive beam forming. Direction of arrival (DOA) estimation with algorithms such as MUSIC, ESPRIT, and CAPON is beyond the scope of this paper [4].

## 5. SWITCHED AND ADAPTIVE BEAM

If the complex weights used are selected from a library of weights that form beams in specific, predetermined directions, the process is called *switched beam forming*. In this process, a hand-off between beams is required as users move tangentially to the antenna array. If the weights are computed and adaptively updated in real time, the process is known as *adaptive beam forming*. The adaptive process permits narrower beams and reduced output in other directions, significantly improving the signal-to-interference-plus-noise ratio (SINR). With this technology, each user's signal is transmitted and received by the base station only in the direction of that particular user. This drastically reduces the overall interference in the system. A smart-antenna system includes an array of antennas that together direct different transmission/reception beams toward each cellular user in the system [1].

Fig 4: beam-forming smart-antennas system

## 6. SMART ANTENNA IN 3G SYSTEMS

Now Smart Antenna Systems are extensively used in wireless communication systems. It is because of the fact that Smart Antennas have the ability to provide high gain in the direction of the desired signal and forming nulls in the direction of the interferences. In this the interference can be reduced and the desired signal can be retrieved. The most crucial step for the Smart antenna system to be used is the selection of the smart algorithms. We can use each algorithm to adjust the weighs of the antenna arrays to form certain amount of adaptive beams to track corresponding users automatically. Presently, many algorithms are applied to the smart antenna systems. Generally there are two categories: Blind algorithms and Non-blind algorithms. [8]

## 7. BLIND ALGORITHM & NON-BLIND ALGORITHM

The algorithm in which a system requires a reference so that to adjust the weights is known as blind algorithm. In case, we know the direction of the signal, we can determine the response of the channel which then leads to the determination of the weights according to some principles. LMS, RLS, SMI, LCMV etc. are included in this algorithm class.

Non-blind algorithm do not require a reference signal, however, in this, transmitted signal is estimated and is seen as the reference signal by the receiver for further signal processing. In this algorithm, the inherent characteristic of the modulating signal which is by nature independent of the carried information is used extensively [8]

## 8. IMPLEMENTING ADAPTIVE BEAM

Adaptive beam forming can be combined with the well known Rake receiver architectures that are widely used in CDMA-based 3G systems, to provide processing gains in both the temporal and spatial domains. This section describes the implementation of a *Rake beam-former structure*, also known as a *two-dimensional Rake*, which performs joint space-time processing. The signal from each receiving antenna is first down-converted to baseband, processed by the matched filter-multipath estimator, and accordingly assigned to different Rake fingers.

The beam-forming unit on each Rake finger then calculates the corresponding beam-former weights and channel estimate using the pilot symbols that have been transmitted through the dedicated physical control channel (DPCCH). The QR-decomposition-(QRD)-based recursive least squares (RLS) algorithm is usually used as the weight-update algorithm for its fast convergence and good numerical properties. The updated beam-former weights are then used for multiplication with the data that has been transmitted through the dedicated physical data channel (DPDCH). [4][5]

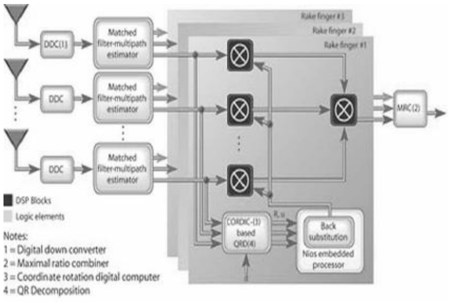

Fig 5: Basic block diagram of adaptive beam forming with FPGA

Maximal ratio combining (MRC) of the signals from all fingers is then performed to yield the final soft estimate of the DPDCH data. Applying complex weights to the signals from different antennas involves complex multiplications that map well onto the embedded DSP blocks available for many FPGAs. The example in Figure 6 shows DSP blocks with a number of multipliers, followed by adder/subtractor/accumulators, with registers for pipelining. Such a structure lends itself to complex multiplication and routing required in beam-forming designs. [7]

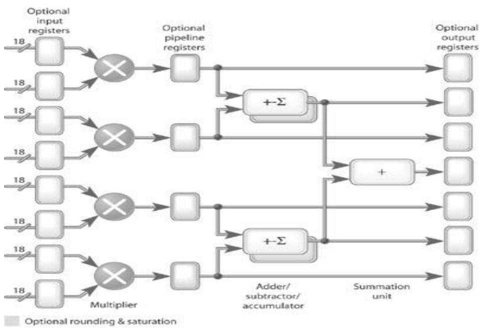

Fig 6: Example of DSP block architecture

## 9. ADAPTIVE ALGORITHMS

Adaptive signal processing algorithms such as least mean squares (LMS), normalized LMS (NLMS), and recursive least squares (RLS) have historically been used in a number of wireless applications such as equalization, beam forming and adaptive filtering. These all involve solving for an over-specified set of equations, as shown below, where $m > N$:

$$\begin{gathered} x_1(1)c_0 + x_2(1)c_1 + \ldots\ldots x_N(1)c_N = y(1) + e(1) \\ x_1(2)c_0 + x_2(2)c_1 + \ldots\ldots x_N(2)c_N = y(2) + e(2) \\ \vdots \\ x_1(m)c_0 + x_2(m)c_1 + \ldots\ldots x_N(m)c_N = y(m) + e(m) \end{gathered}$$

Among the different algorithms, the recursive least squares algorithm is generally preferred for its fast convergence. The least squares approach attempts to find the set of coefficients that minimizes the sum of squares of the errors, in other words:

$$\left\{ \min \sum_{m} e(m)^2 \right\}$$

Representing the above set of equations in the matrix form, we have:

$$X\mathbf{c} = \mathbf{y} + \mathbf{e}$$

Where $X$ is a matrix ($m$x$N$, with $m>N$) of noisy observations, **y** is a known training sequence, and **c** is the coefficient vector to be computed such that the error vector **e** is minimized.

Direct computation of the coefficient vector **c** involves matrix inversion, which is generally undesirable for hardware implementation due to numerical instability issues. Matrix decomposition based on least squares schemes, such as Cholesky, LU, SVD, and QR-decompositions, avoid explicit matrix inversions and are hence more robust and well suited for hardware implementation. Such schemes are being increasingly considered for high-sample-rate applications such as digital predistortion, beam forming, and MIMO signal processing. FPGAs are the preferred hardware for such applications because of their ability to deliver enormous signal-processing bandwidth. FPGAs provide the right implementation platform for such computationally demanding applications with their inherent parallel-processing benefits (as opposed to serial processing in DSPs) along with the presence of embedded multipliers that provide throughputs that are an order of magnitude greater than the current generation of DSPs. The presence of embedded soft processor cores within FPGAs gives designers the flexibility and portability of high-level software design while maintaining the performance benefits of parallel hardware operations in FPGAs [6][9].

## 10. QRD-RLS ALGORITHM

As described in Pattan's book,[1] the least squares algorithm attempts to solve for the coefficient vector **c** from *X* and *y*. To realize this, the QR-decomposition algorithm is first used to transform the matrix *X* into an upper triangular matrix*R* (*N* x *N* matrix) and the vector **y** into another vector **u** such that *R***c**=**u**. The coefficients vector **c** is then computed using a procedure called *back substitution*, which involves solving these equations:

$$c_N = \frac{u_N}{R_{NN}}$$

$$c_i = \frac{1}{R_{ii}}\left(u_i - \sum_{j=i+1}^{N} R_{ij} C_j\right) \text{for } i = N-1, \,..1$$

The QRD-RLS algorithm flow is depicted in Figure 7

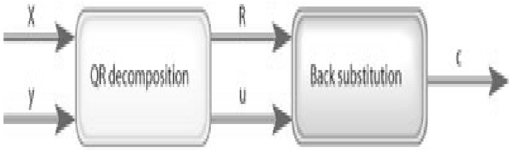

Fig 7: QR-decomposition-based least squares

The QR-decomposition of the input matrix *X* can be performed, as illustrated in Figure 8, using the well-known systolic array architecture. The rows of matrix *X*are fed as inputs to the array from the top along with the corresponding element of the vector **y**. The **R** and **u** values held in each of the cells once all the inputs have been passed through the matrix are the outputs from QR-decomposition. These values are subsequently used to derive the coefficients using back substitution technique [11]. Each of the cells in the array can be implemented as a coordinate rotation digital computer (CORDIC) block. CORDIC describes a method of performing a number of functions, including trigonometric, hyperbolic, and logarithmic functions.

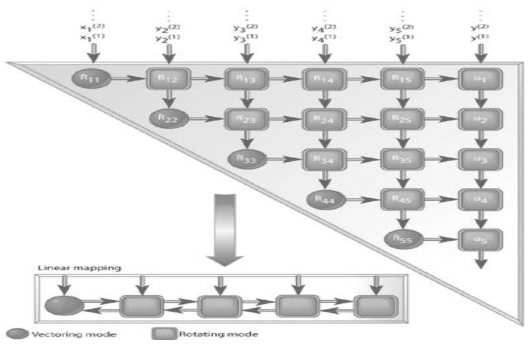

Fig 8: Triangular systolic array example for CORDIC-based QRD-RLS

The algorithm is iterative and uses only add, subtract, and shift operations, making it attractive for hardware implementations. The number of iterations depends on the input and output precision, with more iterations being needed for more bits. For complex inputs, only one CORDIC block is required per cell. Many applications involve complex inputs and outputs to the algorithm, for which three CORDIC blocks are required per cell. In such cases, a single CORDIC block can be efficiently timeshared to perform the complex operations. Direct mapping of the CORDIC blocks onto the systolic array, as shown in Figure 8, consumes a substantial amount of an FPGA's logic but yields enormous throughput that's probably overkill for many applications. In a mixed mapping scheme, the bottom rows in the systolic array are moved to the end of the top rows to make it possible to have the same number of cells in each row. Then, a single CORDIC block can perform the operations of all the cells in a row, with the total number of CORDIC blocks required being equal to the total number of rows. This is called mixed mapping because each CORDIC block has to operate in both vectorize and rotating modes.

## 11. WEIGHTS AND MEASURES

The beam-former weights vector **c** is related to the **R** and **u** outputs of the triangular array as **Rc=u**. **R** being an upper triangular matrix, **c** can be solved using a procedure called back substitution. As outlined in Haykin and Zhong Mingqian et al., the back-substitution procedure operates on the outputs of the QR-decomposition and involves mostly multiply and divide operations that can be efficiently executed in FPGAs with embedded soft processors. Some FPGA-resident processors can be configured with a 16x16 -> 32-bit integer hardware multipliers. The software can then complete the multiply operation in a single clock cycle. Since hardware dividers generally are not available, the divide operation can be implemented as custom logic block that may or may not become part of the FPGA-resident microprocessor [1].

## 12. SMART ANTENNAS TO ENHANCE THE SYSTEM PERFORMANCE

Most of the research effort on the use of adaptive antennas in mobile communications has been concentrated on the base station antennas. The objective of adaptive beamforming is to maximize the signal to interference and noise ratio of the received signal, by maximizing the strength of the desired signal while reducing the adverse effects of interference sources. Although it is a practical and effective technique for reducing the effect of multipath fading, it is rarely used at a mobile station due to cost, size and available power of the mobile station. A single base station often serves hundreds to thousands of mobile stations. Therefore it is more economical to add equipment to base stations rather than the mobile stations. However, with operators and manufacturers preparing and deploying the third generation systems, the increasing growth of mobile phone users has created a need for even higher capacity in cellular network. One way of overcoming the capacity problem could be by using multiple adaptive antennas on the handsets [10]. In addition to the higher capacity benefit, this may offer improved efficiency in the following areas

- ❖ reduction of multipath fading
- ❖ suppression of interference signals
- ❖ improvements of call reliability
- ❖ lowering the specific absorption rate
- ❖ mitigation against dead zones
- ❖ increased data rates
- ❖ Spectral efficiency

The main goal of the mobile operators is to provide new and better services in view of cost effectiveness. The main problem in 3G technologies such as UMTS and CDMA2000 is the shortage of network resources. Implementing more base stations is not a feasible and better solution. Similarly, cell splitting with more sites extensively reduces the throughput per site due to the co-channel interference. Smart Antenna can help greatly to solve this problem because the use of smart antennas in wireless networks is well known to increase the number of voice calls and the amount of data throughput. This is because of the fact that the smart antennas reduce the effects of interference and in this way ease the network management. The BS which is equipped with smart antenna has the ability to track the MS by measuring the relative signal strengths at multiple antennas. In this way, smart antennas increases capacities which in turn provide more profit because of the efficient use spectrum and power. The spectrum and power both depends on the antenna's radiation and reception pattern. Increase in capacity along with the provision of the QoS services are the main benefits of the deployment of the Smart Antenna Systems. [3]

## 13. SMART ANTENNA SYSTEMS IN 3G SHARED CHANNELS

In 3G system, the use smart antennas enhance the user capacity which in turn increases system packet data throughput. Shared channels are used in 3G systems to transfer that are delay tolerant such as email or other downloads. On such channels, users share code resources and scheduling algorithms. There are two smart antenna concepts; adaptive beamforming in which beams are pointed to the desired user and fixed beam switching in which fixed preformed antenna beams are assigned to the user. It has been observed that the use of beamforming antenna with four antenna elements increases the throughput over 100% in relation to the three sectors approach. On the other hand, the fixed beam switching even shows more positive results as the adaptive beam antennas are more sensitive to the link degradation caused by poor channel estimation. [1]

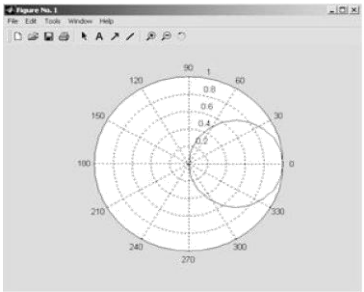

Fig 9: simulation of adaptive beamforming Smart Antenna at 0˚

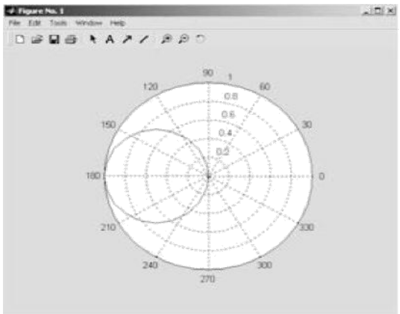

Fig 10: simulation of adaptive beamforming Smart Antenna at 180˚

## 14. CONCLUSION

In this paper, characteristics and efficiency factors of the smart antennas are comprehensively discussed. The Smart Antenna Systems can prove to be efficient antenna systems for the 3G communication systems such as UMTS and CDMA2000. These communication systems are facing shortage in the network resources which can be compensated by the use of Smart antenna as it has the ability to enhance the capacity as well as the user throughputs. Also it can track the desired user to transmit the maximum power in the right direction. These are the major factors of the efficiency of the Smart Antenna

Systems. Major network operators are looking forward to deploy Smart antennas because of its efficiency to enhance the user capacities and ultimately the throughput.

Smart-antenna technology requires a lot of processing bandwidth, in the neighborhood of several billion multiply-and-accumulate (MAC) operations per second. Such computationally demanding applications can quickly exhaust the processing capabilities of many DSPs. Some FPGA chips with embedded DSP blocks, on the other hand, provide throughput in excess of 50 GMAC/sec, offering a high-performance alternative for beam-forming applications. There are a number of beam-forming architectures and adaptive algorithms that provide good performance under different scenarios, such as transmit/receive adaptive beam forming and transmit/receive switched beam forming. FPGAs with embedded processors are flexible by nature, providing options for various adaptive signal-processing algorithms.

The standards for next-generation networks are continually evolving and this creates an element of risk for beam-forming ASIC implementations. Transmit beam forming, for example, utilizes the feedback from the mobile terminals. The number of bits provided for feedback in the mobile standards can determine the beam-forming algorithm that is used at the base station. Moreover, future base stations are likely to support transmit diversity, including space/time coding and multiple-input, multiple-output (MIMO) technology. Since FPGAs are remotely upgradeable, they reduce the risk of depending on evolving industry standards while providing an option for gradual deployment of additional transmit diversity schemes.

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