# Polygonal Dipole Placements for Efficient, Rotatable, Single Beam Smart Antennas in 5G Aerospace and Ground Wireless Systems

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***Abstract*—In telecommunication systems and radars, the common practice in using array antennas is to place a reflector behind the array so as to reflect the backward signal also in the forward direction. Moreover, in the 5G wireless systems, smart antennas, especially those with a single beam, are expected to play a critical role in its successful launching in 2020. We show in this paper that a linear array antenna necessarily ends up with symmetrical beamforming on both sides of the array axis. Thus, single direction (forward direction) beamforming cannot be achieved by placing the electromagnetic radiators (e.g. dipole elements) in a straight line. We propose that in situations where a smart array structure demands single rotatable beams, that single rotatable beamforming can be achieved by changing the geometrical shape of the array. However, the computational intensity involved in finding optimized weight coefficients for beamforming over the entire 360o space turns into the major challenge. In order to minimize the computational repetition of optimizing weights for every direction, a regular polygon array antenna is proposed. We show that an array antenna placed in a regular polygon yields a smart antenna with a highly effective and computationally fast, reduced memory and electronically rotatable single beam.**

***Index Terms*—Smart Arrays; Beamforming; Array Structure.**

## I. INTRODUCTION

Wireless communications systems are prone to multipath phenomena and other impairments which can adversely affect their performance. A highly reflective environment would create primary and secondary reflected waves that interfere with a mobile user [1]. The problem is worsened with a smart antenna on a mobile station as well, as required by the 5G wireless system. While base stations in a highly reflective environment have a capability to use multiple waves to improve signal quality, this feature is not available in simple mobile devices which are used in highly reflective environments. Smart antennas hold great promise to surpass the communications challenges in highly reflective environments to provide reliable communications in emergencies and for mm-wave 5G technology [2].

Smart antenna research and development has largely focused on elements placed in a straight line. Such a linear antenna geometry produces a main beam and an image along the central array axis [3]-[5] The drawback of such an antenna is more significant at the receiving end, where reflected waves from both sides of the axis will be received and processed, degrading signal quality and performance. Therefore, we propose a single beam smart antenna with single beam acceptance at the receiving end, nullifying all other signals. We show that the possible, computationally efficient arrays with multiple numbers of element which will yield a rotatable single beam is an array with a polygonal geometry. Some different and complex smart antenna geometries were proposed and analyzed by others; however, the elements were arranged in a linear form with inefficient use of power [4], [5].

In Figure 1, it is shown a sixteen element (8 x 8) array antenna which produces a single steerable antenna beam. At the back of the patch array antenna is a ground plane over which the patch elements are placed as shown in Figure 2. The ground plane in the case of patch antennas acts as one part of a parallel waveguide to steer the signals to (when transmitting) or from (when receiving) signals. When such an antenna is used in the aerospace industry, for instance, the antenna needs to be placed on the fuselage of the aircraft. In the specific case shown in Figure 2, the antenna is placed on the top part of the center fuselage, for aircraft to satellite communication, where the satellite orbits, say, at an altitude of 800 km whereas the aircraft flies at 20 km altitude. For aircraft to ground communication, another antenna needs to be placed on the bottom of the fuselage, away from parts such as the landing gear to avoid obstruction of the transmitted or received electromagnetic signals.

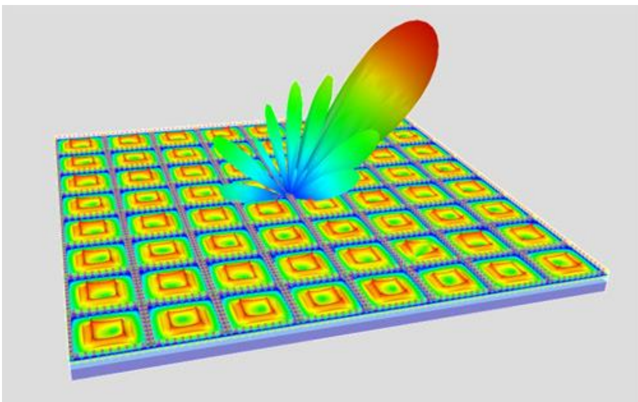


Figure 1: A Single beam 8x8 Array Antenna [6]

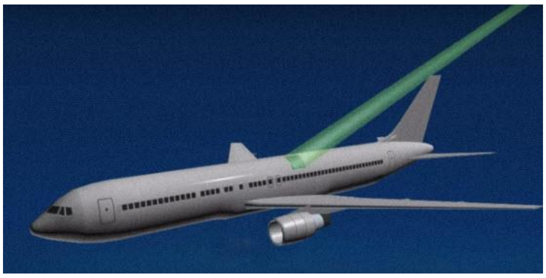


Figure 2: Antenna Placed on Center Fuselage [7]

However, as shown in Figure 3, the aircraft needs to communicate with several objects simultaneously. A single aircraft is in a position where it needs to communicate or, in the case of safety and defense, be transmitting radar signals from one or several antennas which can directly look at all other objects (in this case two commercial aircraft, one helicopter, a satellite and towards the ground). Instead of loading the aircraft with several array antennas placed on various parts of the fuselage and Radom, the better option will be to minimize the needed number of array antennas (each with its own transmission and receiver electronics and power supply) it is best to minimize the number of antennas with smart antennas that may be placed anywhere on the body of the aircraft (e.g. on top of the tail fin) allowing it to use a rotatable beam that is intelligently rotated by electronic beamforming, to look in several directions with a rapidly rotatable beam that has no reflector or guiding surfaces behind it. The antenna we have proposed is such an antenna that produces rotatable, single beam antenna requiring minimum power without any need for a reflecting or guiding surface behind it.

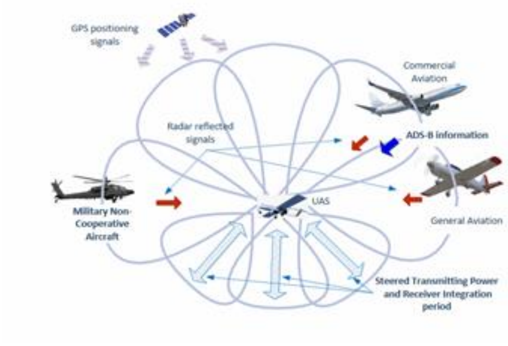



Figure 3: Multiple access model [8]

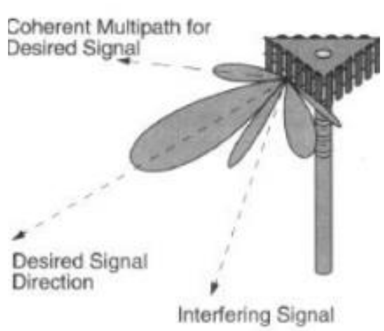



Figure 4: In a land wireless system, the stationary base station (BS) antenna has three sectors to cover the entire area around the BS [9]

The aircraft at the center needs several antennas on the fuselage to be able to look at other vehicles or objects. An alternative is a single beam antenna that may be placed at any point that will give it 360º view of the space around it.

A similar need for land-based wireless communication systems arises in the case of smart antennas for land wireless systems, as shown in Figure 4. In this case note that three sectors, with each sector containing an array of antennas with a reflecting surface behind each, is required to produce steerable beams that may cover all 360º around the base station on top of the base station tower [10]-[12].

Using the single beam, rotatable antenna proposed herein, without any need for reflectors, we have a powerful smart antenna that may cover the regions covered by all three sectored smart antennas with reflectors behind the antenna elements for each sector [12], [13]. Moreover, in future systems where the entire base stations may be done away with, where the mobile handsets have to take over the functions of the present-day static base stations, the need for such an antenna as proposed herein becomes critical.

## II. 5G Wireless Systems and Smart Antennas

Amongst the major challenges facing the future wireless systems are the following [14]:

1. Very fast data transfer for user interaction (including the health, office and entertainment services), e.g. 5 Gbps, with instantaneous connectivity wherever they are and whenever the need to connect.
2. Uninterrupted service at places where a large crowd of people is using the wireless system, such as at supermarkets, airport, stadiums and mass public meetings.
3. Interconnections between people as well as a large number of machines (machine to machine M2M), such as electric distribution system and electric generators, or devices (device to device or D2D).
4. Communication with not only static and slowly moving mobile devices (UDs) but also high quality of service (QoS) to fast moving users such as in trains and fast-moving cars.
5. Reliable connections in M2M and D2D real-time operations, including robotics and self-driving vehicles.
6. Virtual reality in business and office, where about 10 individuals may need to communicate with each other with 3D virtual reality where the individuals located in the same building or outside need to interact and update the single scene being considered.
7. Communication takes place in a dense environment, such as when many vehicles are waiting at a traffic light and all turn on the mobile devices to communicate or surf the internet.
8. In public areas such as malls, galleries and catering areas where the communication system provides service to customers as well as interconnecting commercial (e.g. cash desks, electronic payment) and operational services (e.g. fire protection, CCTV surveillance and automatic doors).
9. Places of large gathering such as a stadium where at some points a vast number of those present want to communicate through their multimedia content to others elsewhere.
10. Teleoperation, control and protection of the smart electric power grid where generator stations, substations, and loads.
11. Alternative route checking, multimedia entertainments

and communication of several cars caught in a traffic jam.

12. Real-time mobile computing from stationary, slowly moving and fast moving vehicles.
13. Good, reliable communication of high definition video clips to be communicated at an open-air festival, where a high density of active users with an aggregated data traffic of about 900 Gbps/km$^2$.
14. Emergency communication such as when people are trapped inside collapsed buildings needing to communicate and identify their locations to be rescued, maintaining connectivity and low battery power usage for many days with the switch on periods that last only for ten seconds.
15. Wireless network for interconnection of a massive number of sensors and actuators, where data transfer is not continuous but at certain required times only with message lengths of 20 to 125 bytes.
16. Road safety and traffic efficiency, reducing the annually increasing number of fatal accidents, e.g. 40000 annual deaths related to traffic accidents, and about 2 million road accident injuries each year.

At the commencement of mobile wireless communication systems, the first generation (1G) systems operated at a data rate of 10 kbps, with a bandwidth of 10-30 kHz using FDMA with only voice communications. The 2G systems using GSM had a data rate of 9.6 kbps, using both FDMA and TDMA for voice and text data transfer. The 3G systems with a 5 MHz bandwidth, operated at a data rate of 50 Mbps providing integrated voice and mobile internet services. The 4G wireless technology provided a peak data rate of 100 Mbps using OFDMA and SC-FDMA allowing for mobile multimedia communication with a high capacity [15, 16]. The fifth generation (5G) wireless systems have the capacity to expand into a wide variety of applications including smart mobile communications, smart homes, smart stores, connected cars, smart office, smart electric power grid, smart cars, smart rooms, high-speed mobile internet, internet of things (IoT), augmented reality and virtual reality. Its preprocessing module will handle transmission, beam and transmission power, interference cancellation and control. Its scheduling algorithms optimize the performance of a large number of mobile stations. With the IoT using the 5G mobile (as opposed to fixed) wireless system will be servicing tens of billions of users with a mobile data transfer that will grows at 24 Exabyte ($10^{18}$ bytes) per month. Peak data rates will be in the range of 10 to 50 Gbps. Whereas the latencies for the 4G systems for end to end and over the air are 50 ms and 10 ms respectively, for the 5G system the corresponding values will be 5 ms and 1 ms respectively. It will allow for simultaneous connections of a very large number of mobile and stationary devices. The new technology will address two key needs of the 5G system: array antennas and small cell base stations (SBS). Whereas the older wireless mobile communications were designed for 1 km x 1 km or 10s of km x 10s of km, several SBSs which are Picocells, femtocells and ultra-dense small cells are placed together to cover 10s to 100s of meters ground area. The SBS is crucial to achieve large network capacity and data rates of the order of 50 Gpbs. By operating alongside the larger mobile base stations (BS) the femtocell SBSs (FSBSs) installed in houses and offices provide an extra layer of HetNets resulting in high quality of service (QoS), with better energy efficiency, capacity and coverage. They may be installed by the customer, and are low cost and small devices of sizes of around 200 mm x 200 mm x 50 mm. Inside houses and office buildings the users (and user equipment, UE) will be expected to be stationary or move slowly, making it easier to track them and beam form to keep up with the low user mobility. Moreover, they will be clustered in certain areas of the building or room. This also means that a decision needs to be made whether to use an array antenna with rotatable beam or use a fixed beam phased array. The short distances between the SBS equipment and the UE will also mean the angular spread of the UE will be large. The antennas used should be low cost and simple. Cost will be lower in general since the power is low, the cost of power amplifiers will be low. Form factors and mutual coupling effects between array antenna elements should also be kept low [15], [16]

Smart antenna systems are critical to future wireless systems to increase maximum range of the system and increase the system capacity (bits/sec/Hz/unit-area). Increasing the system capacity allows for more customers to be serviced at high quality of service and at reduced costs. A smart antenna consists of two basic modules. These are an array antenna and signal processing of signals to transmitted from or received by each element of the array antenna. Hence it is also called an adaptive signal processing antenna. By allowing for spatially selective transmission and reception, as shown in Figure 5, it allows for Space Division Multiple Access (SDMA) which when used with currently multiple access techniques such as frequency division multiple access (FDMA), time division multip0le access (TDMA) or Code Division Multiple Access (CDMA) in provides a high versatile and spectrum efficient system. Two users (the pedestrian and the vehicle) are serviced simultaneously from a smart antenna located at a single position; since the two main beams are spatially separated the same frequency band may be used for both users without any interference.

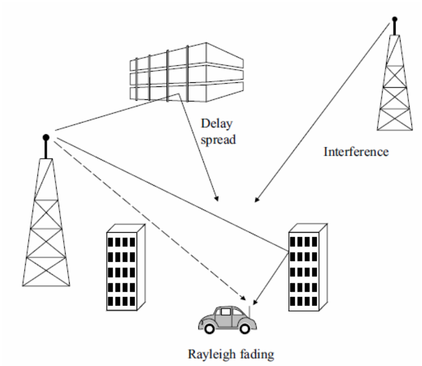



Figure 5: Smart Antenna and Wireless Communication Desired and Undesired Signals [17]

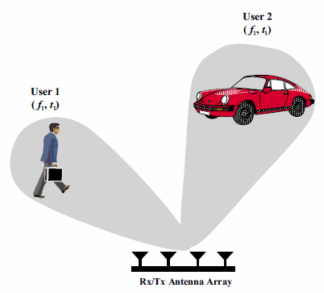
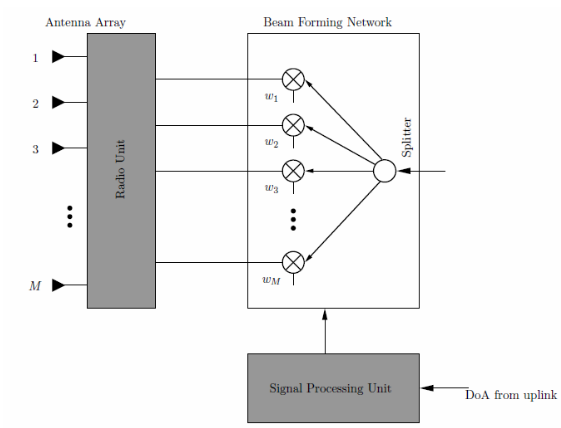



Figure 6: The Smart Antenna and Space Division Multiple Access (SDMA) [18]

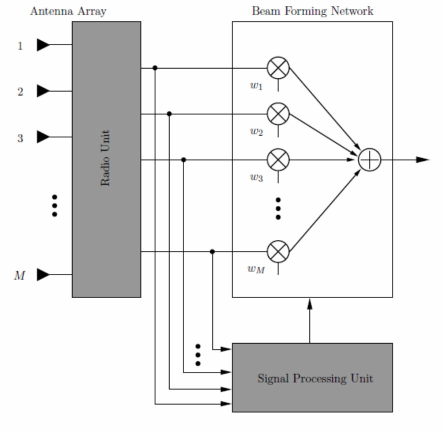
As the users move, and change positions, as shown in Figure 6, and their positions are constantly identified the beams may be redirected to sustain communication with both users. By keeping the user at the peak radiation direction of the beam, maximum signal quality is maintained. The beamforming signal processor does the dynamic changing of the direction of the beams. It is noted that it is hard to get a perfect single beam, and the small minor beams (side lobes) are undesired beams which give rise to wasted power and possible interference generating presence at the smart antenna. Minimizing the presence of these unwanted side-lobes is a challenge.

The signal processor mostly operates on the amplitude of the signal and/or the phase angle of the signal. Smart antennas or adaptive beamforming antennas result in an increase in antenna range and coverage, improved quality of the transmitter to receiver link including link reliability since it allows for Space Division Multi-Access (SDMA) smart antennas also allow for significant improvement in spectral efficiency, allowing for frequency reuse from a single transmitter or receiver. In comparison to Omnidirectional antennas or wide beam antennas where the transmitted power is spread over a large area with much of the area not requiring transmission, the narrow and focused beam of the smart antenna allows for much-reduced power to reach a receiver at the same distance from the transmitter. This means a battery of much lower power is adequate, resulting in significant cost reduction related to low power requirement [17]. With the ability to focus the antenna beam on to a narrow region to form the link with the desired transceiver, the smart antenna suppresses interference from transmitters outside its narrow beam, thus resulting in increased channel capacity. Although the antenna elements used could be single, static Omnidirectional antennas or printed circuit board (PCB) antennas with low gain, more advanced and array antennas can move away from fixed radiation patterns to more focused, rotatable beams. The PCB diploe is cheap, low profile and Omnidirectional. But other antennas increasingly used include the microstrip patch antenna which is easy to fabricate and has a half-wavelength resonant frequency, the planar inverted F (PIFA) antenna is physically small and has a quarter wavelength resonant frequency and the E-plane horn antenna with moderate directivity has a high bandwidth [19].

Figure 7 shows the adaptive or smart antenna transmitter (Figure 7(a)) and receiver (Figure 7(b)).




(a)




(b)

Figure 7: Smart Antenna (a) Transmitter and (b) Receiver [16]

Antenna beamforming is achieved by combining signals received by each element of the antenna by constructive or destructive mixing of the signals after multiplying the signal received by each element by a weight that is complex (amplitude and phase changing weights). Shown in Figures are the trainmaster and receiver modules of a smart antenna

The weights depend on the channel state information (CSI). The CSI depends on several features of the channel or medium over which the wireless signal has traveled, including fading, scattering, power decay and noise. If the weight by which the signal received by an element of the array antenna is multiplied changes only the phase of the received signals, then while the beam is angularly shifted, its overall antenna array factor or pattern remains the same. If the weight also changes the amplitude of the received signal at each element, then the overall pattern is also changing. Since the uplink and downlink channel frequencies differ, the CSI for both uplink and downlink are not expected to be the same since the CSI is frequency dependent. Fading, for instance, is frequency selective. Its attractive features, in addition to increased capacity, interference suppression, and longer range coverage, it can track multiple mobile stations, reduces multipath fading, bit error rate and the probability of link loss and co-channel interference. Heterogeneous networks (HetNets) allow for cell size reduction resulting in greater BS spectral efficiency [2]. Such spatial densification using several elements in the SBS array antenna with a high density of SBS per square meter and spectral aggregation allows for network densification.

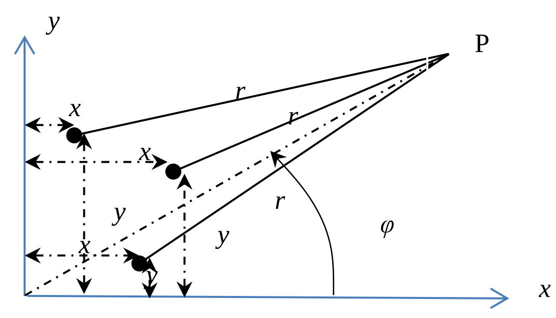



Figure 8. Schematic diagram of dipole placement

### A. *Symmetrical Beams: Dipoles on Straight Line*

When all dipoles are placed in a straight line, the radiation pattern is symmetrical along the axis of dipole placement [18]. Consider now the dipoles placed as shown in Figure 8. The respective complex current phasors of the dipoles. $I_1$, $I_2$, and $I_n$ yield the following electric far-field at the observation point P:

$$E = A_0 I_1 e^{-j\beta r_1} + A_0 I_2 e^{-j\beta r_2} + \ldots + A_0 I_n e^{-j\beta r_n} \qquad (1)$$

where $A_0$ and $\beta$ are a constant and the phase constant, respectively. Substituting for $r_1$, $r_2$, to $r_n$ in terms of the distance $r$ of P from the origin, and setting $w_n = A_0 I_n e^{-j\beta r}$ and $y_1 = y_2 \ldots = y_n = 0$ for dipoles in a straight line

$$E(\varphi) = w_1 e^{j\beta x_1 \cos\varphi} + w_2 e^{j\beta x_2 \cos\varphi} + \ldots + w_n e^{j\beta x_n \cos\varphi} = E(-\varphi) \qquad (2)$$

Symmetry is observed from $E(-\varphi) = E(\varphi)$. Hence weights will not exist for a single electric beam on one side of the $x$-axis. A solution exists only for weights for a single electric beam in the positive/negative direction of the $x$-axis (the end-fire array) [10]. But this single beam cannot be rotated in other directions. Therefore, rotatable single beam in any and every direction cannot be obtained by means of weight optimization when all dipoles are in a straight line. Thus for instance, in the broadside array, beams will exist in both directions perpendicular to the array axis [10].

### B. *Geometrical Placement of a Single Rotatable Beam*

Since the straight-line dipole placement model is not appropriate for getting a single beam antenna, we propose here that the individual antenna elements (e.g. dipoles) be not placed in a straight line, but in one of the forms shown in Figure 9 and 10. It is evident from the proposed model that the minimum number of dipoles for single beamforming is three [12]. However, with more elements will ensure a narrow beam with the desired shape.

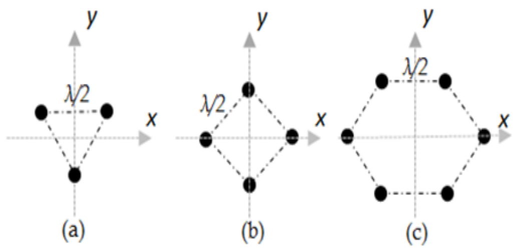



Figure 9: Schematic diagram of array models

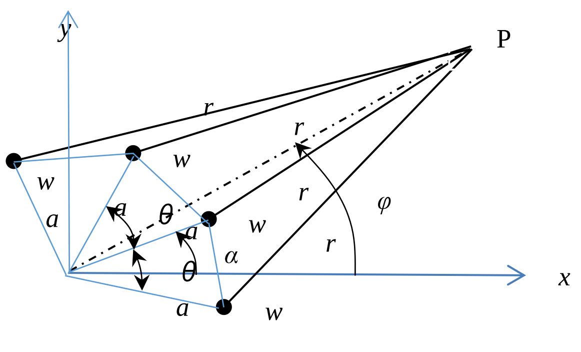



Figure 10: Dipole placement in a regular polygon

When the polygon has $N$ sides, the angle between two vertices from the center of the polygon; $\theta$ is $2\pi/N$. The electric field at point P for the dipoles given in Figure 10 can be written using (2) and simplified to:

$$E(\varphi) = w_1 e^{j\beta a \cos(\alpha-\varphi)} + w_2 e^{j\beta a \cos(\theta+\alpha-\varphi)} + w_3 e^{j\beta a \cos(2\theta+\alpha-\varphi)} \ldots + w_N e^{j\beta a \cos((N-1)\theta+\alpha-\varphi)} \qquad (3)$$

For arbitrary weight values, the electric field at point P can be calculated from the equation (3). For convenience, in Figure 10, we name the element with weight $w_N$ as the 1st element, that with weight $w_1$ as the 2nd element, etc. Now we can rotate the weights such that the 2nd element with weight $w_1$ and the 3rd element with $w_2$ and the final *1st* element with weight $w_N$. For the new weights values, the electrical field can be obtained using (3) as modified to what is given below:

$$\bar{E}(\varphi) = w_1 e^{j\beta a \cos(\theta+\alpha-\varphi)} + w_2 e^{j\beta a \cos(\theta+\theta+\alpha-\varphi)} \ldots + w_{N-1} e^{j\beta a \cos(\theta+(N-2)\theta+\alpha-\varphi)} + w_N e^{j\beta a \cos(\theta+(N-1)\theta+\alpha-\varphi)} = E(\theta+\varphi) \qquad (4)$$

Therefore shifting weights through the adjacent vertices, the entire field pattern could be shifted by the same angle $\theta$. This characteristic will help us to rotate the beam in steps by an angle $\theta$ without recalculating weights. It is only possible when the dipoles are placed at the vertices of a regular polygon. It is such a computationally efficient arrangement of the array antenna elements, without any need to recalculate the weights for the new positioned to which the single beam needs to be rotated to, that will meet the demands of the new generation of smart antennas needed for future wireless systems, as set out in recent publications [5], [12], [20].

## III. Results

In this section, we shall implement the above polygonal array design to demonstrate the single beam and its control. Using LMS optimization for a 3 and 6 elements array models as shown in Figure 11(a) and 11(b), we get a single beam in the desired angle direction of 60° in both cases. Having rotated the coefficients calculated for 60°, we can again rotate the beam to 180° and 300° for 3 elements as shown in Figure 11 (a) and 120°, 180°, 240°, 300° and 0° for 6 elements as shown in Figure 11 (b).

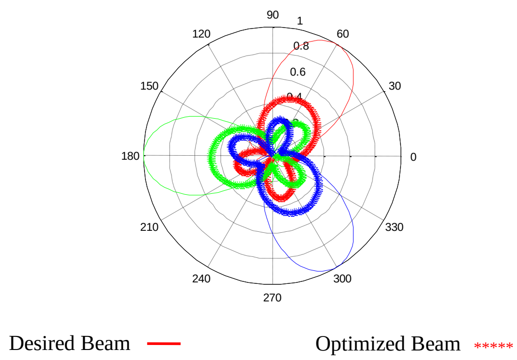



Figure 11(a): Rotated beam to 60°, 180° and 300° with 60° weights

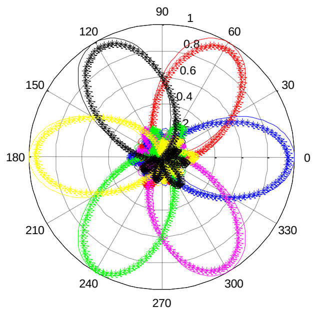



Figure 11(b): Rotated beam to 60°, 120°, 180°, 240°, 300° and 0° with 60° weights.

Hence by optimizing the weights for a single angle, we can rotate the beam to three different angles (or more) by simply phase shifting the weights without recalculating them by, for instance, the LMS method. Thus we have verified that the set of optimized weights coefficients for a single angle (60°) can be used for a specific set of directions without repeating the optimization computation for a new set of desired directions. This is true for any array where the dipole elements are placed at the vertices of a regular polygon.

## IV. CONCLUSIONS

The need for a rotatable single beam, smart array sensors and antennas is increasing with greater demand for data rate and mobile station centric rather than base station centric mm wireless systems. In this paper, it is shown that there is a need to move away from the conventional straight line, linear array antennas or sensors. Instead, it is shown that a highly effective, single steerable beam array antenna may be achieved with the array elements placed at the vertices of an equilateral-triangle or at the vertices of any regular polygon. Furthermore, the computational burdens in the process of single beamforming in all directions are significantly reduced by the proposed regular polygon array smart antenna.

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