Linear Smart Array Antenna Configurations for a Transceiver in a Multi-Signal Environment

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Abstract—**Future smart antenna technology requires multi-element, adaptive array antennas to be placed on very small cell phone units. Small adaptive array antennas require heavy signal processing if the statistical techniques are used to maximize radiation in the desired direction and to null the beam in the direction of interfering signals. In terms of weight, battery energy and computational memory and time required it is imperative to minimize computational time, memory required and weight of the hardware to be used for adaptive beamforming in smart antennas. In this paper is presented a three-element antenna that uses analytically solved weight computation. No statistical or number crunching techniques are used. Moreover, it is shown that the antenna elements behind which two signal processing units are placed are critical. The placement of the weight processing signal processing units is critical for obtaining simultaneous beam maximizing towards the desired direction and nulling towards the interferer direction.**

Index Terms—**Smart Antenna; 5G Communications; Adaptive Signal Processing.**

I. INTRODUCTION

Adaptive Array Antenna, also called Smart Antenna, technology is already playing a key role in the 4G wireless communication system. It is expected to play a key role in the future 5G wireless systems [1-4]. This paper focuses on the placement of signal processing element on the array elements so as to minimize computational burden by avoiding heavy statistical signal processing to obtain the ideal beam of a mobile station, or the beam directed towards a mobile beam. The paper shows that in a three-element array antenna, for instance, the position or placement of two signal processors that adjust the weights to get the desired beam, determines the versatility of the array antenna in being able to simultaneously maximize the beam towards the desired geographical point and minimizing the beam towards an interference source. It should be noted that minimizing the signal processing hardware on the smart antenna, for instance using two signal processor units rather than three on a three-element array, and using an analytical solution to maximizing and/or minimizing the beam in given directions, will significantly simplify the array antenna so as to allow it to be placed on the mobile unit in addition to having a smart antenna on the base station. The smart antenna is critical to reduce multipath fading, cancellation of interference signals, to get better call reliability, to have strong signals even when crossing cell boundaries, to increase data rates and to have efficient spectral usage by allowing a single carrier frequency

to be used for more than one user in a single cell [5,6].

In multiplexing based on beam forming the knowledge of the channel is needed for closed loop transmission, where the beam is matched to each data pipe. Peak and average data rates are increased by multiple layer beamforming. Moreover, multiple-input-multiple-output (MIMO) systems are used to improve beamforming towards the edge of a cell. Massive MIMO systems will be used in the 5G BS for frequencies above 6 GHz, with a ten times faster data rate than 4 G system; e.g. 100 MBs with a delay of about 1 ms. At 15 GHz, the data rate will reach up to 14 GBs with a large density of MSs. In joint beamforming MIMO systems, two or more base station antennas jointly transmit signals to a single mobile station. Incoherent joint beamforming, signals from multiple BSs are combined at the MS. The drawback is that such a system is sensitive to channel state information (CSI). In non-coherent joint beamforming, it is difficult to cancel interference from multiple BSs. In MIMO systems with coordinated beamforming beam scheduling and beamforming are aligned over the BSs to reduce interference at the MS. But this does not lend itself to joint decisions of MS. MIMO antennas with spatial multiplexing (SM) allows for multi-layered HetNets and densification. In an M x N channel MIMO antenna, where M is the number of receive antennas and N is the number of transmit antennas, the capacity depends on M, N and correlation between the channels. The channel capacity reduces with increasing correlation. Correlation, in turn, depends on both spatial correlation and inter-element mutual coupling and distance between the elements. Thus, correlation depends on the inter-element distance and the amount of signal scattering in the area in which the SBS MIMO antenna operates. The number of elements will be affected by the overall size of the small cell and the frequency of operation. If the wavelength of the carrier frequency is λ mm, then the inter-element distance is λ/2 mm, the number of elements that may be used is about 200 mm/(λ/2) for a 200mm size SBS. MIMO antennas with spatial multiplexing (MIMO-SM) at both BS and UE can significantly increase data rates. Interference of SBS with neighboring SBS may be reduced by using power control, resource partitioning and interference mitigation. Massive MIMO systems can use from 8 to 256 elements to get link budget gain of 9 dB and 24 dB respectively [7-10].

The top end of challenge to the new 5G wireless systems is in applications such as in military combat. The same system could be used in unmanned autonomous vehicle (UAV) to UAV communication. In such situations, where for instance, a battalion moves into high-risk combat area it will need to

ensure secure and fast information data transfer between the members of the battalion while the signal dies out to any outside listener to conversations, text, image and video transfer of critical data to the whole battalion. In such cases short range soldier to soldier communications at very high data rate is needed, at frequencies around 60 GHz. The wireless systems will be body worn with a variety of sensors seeking to transfer information over it, including real-time streaming video cameras to biochemical sensors and night vision infrared sensors. The array antenna could be cylindrical or non-linear array antennas. The energy consumption needs to be minimal since it may need to reliably operate over a long period of time on the battlefield with little opportunity to recharge batteries. It needs to transmit signals without being detected, robust and secure, operating in urban areas where clutter will be large. All the communication devices will be MSs without any BSs, and thus the system needs use MSs as a BS that connects the MS of each soldier. The advantage of 60 GHz system will be mm-sized devices that are wearable operating at high data rates in unused frequency spectrum with ultra-wide bandwidth of about twenty percent of the carrier frequency. Transmission schemes could use the single carrier system frequency domain equalization (SCFDE) scheme or OFDM orthogonal frequency domain multiplexing. The system has to be resistant to jamming and operate in marginal conditions with low battery power and energy demand. Reliable computer-based simulation of these scenarios, using reliable channel models, is much needed to develop and test systems before trying out expensive hardware prototypes. Part of the objective of the design of a superior array antenna is that it could also be used in the computational simulation testbed needed in the development of future wireless systems. As the frequency of operation is increased to the vacant spectrum in the 28 to 38 GHz (attenuation of about 0.06 dB/km) and 70 to 80 GHz bands (attenuation of about 0.3 dB/km), the challenges of high path loss and high rain and atmospheric attenuation are challenging problems. At these frequencies Doppler frequency shifts also become significant. These stringent requirements on the 5G smart antennas and beyond, need careful, scientific modelling and signal processing of the antenna electromagnetic fields [11-13]. The new three element antenna, with which simultaneous maximizing in one direction and nulling in another direction may be obtained, is a promising smart antenna for the new 5G wireless systems of the future [14].

II. THE THREE-ELEMENT SMART ANTENNA

We shall now consider two different three-element array smart antennas, as shown in Figure 1, called SA1 and Figure 2, called SA2. The difference between the two is that in SA1 the two signal processing modules are behind array elements 2 and 3. In SA2, the signal processing modules are placed behind antenna elements 1 and 3. We shall show that SA2 allows for simultaneous maximizing and minimizing of the beams in two different directions each. But with SA1 such simultaneous maximizing and beam minimization in two different directions cannot be achieved simultaneously.
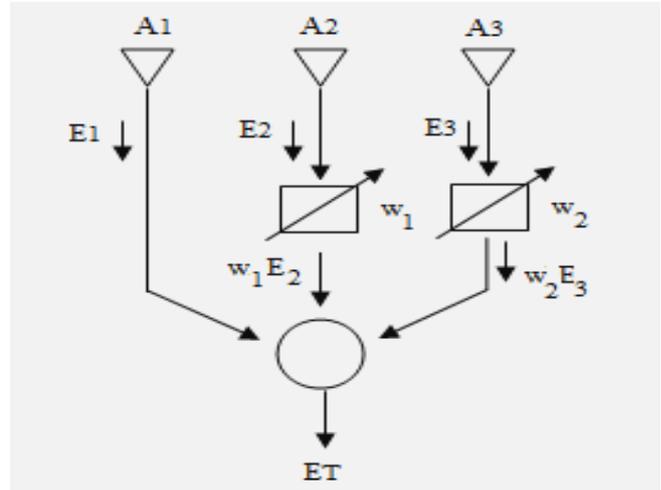
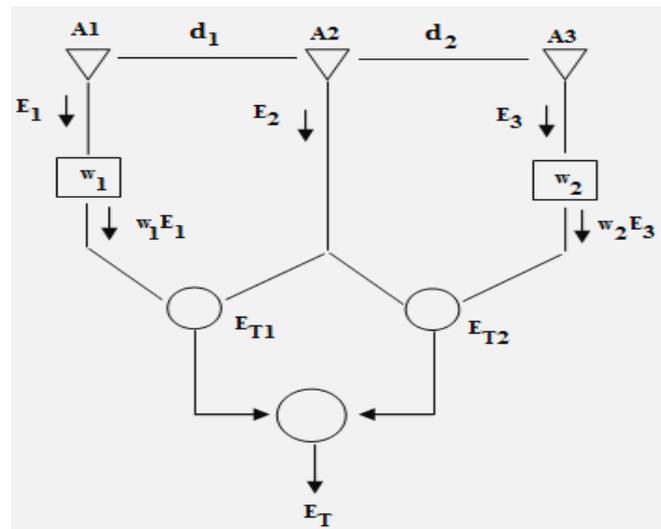

Figure 1: Three element Smart Antenna SA1

Figure 2: Three element Smart Antenna SA2 [14]

For the 3-element array configuration shown in Figure 1, at the output of the antenna elements A_2 and A_3 are the digital beam steering (beamforming) weights "w_1" and "w_2" which must be set together either to maximize the mobile station (MS) antenna beam toward the Base Station (BS) antenna or to create a null in the direction of an interring signal (e.g. from another BS or MS).

The total electric field output will be:

$$E_T = E_1 + w_1 E_2 + w_2 E_3 \qquad (1)$$
$$E_T = E_1 + e^{j\delta} E_2 + e^{j2\delta} E_3 \qquad (2)$$

where assuming w_1 and w_2 have magnitude "1". The normalized N-element array factor equation is given below [2]:

$$AF_N = \frac{1}{N} \left| \frac{\sin \frac{N\psi}{2}}{\sin \frac{\psi}{2}} \right| \qquad (3)$$

where $\psi = kd \sin\theta \cos\emptyset + \delta$

Therefore, the array factor of the 3-element array is:

$$AF = \frac{1}{3} \left| \frac{\sin\frac{3\psi}{2}}{\sin\frac{\psi}{2}} \right| \qquad (4)$$

The maximum values of the array factor occur when [10]

$$\frac{\psi}{2} = \pm\, m\,\pi, \qquad m = 0,1,2,\dots$$

$$\psi = \pm\, 2\,m\,\pi, \qquad m = 0,1,2,\dots$$

Therefore:

$$\delta = \pm 2\, m\,\pi - kd\, \sin\theta_d \cos\emptyset_d \qquad (5)$$

The null/zero values of the array factor occur when [2, 10]

$$\psi = \frac{2}{N}\, m\,\pi, \qquad m = 1,2,3,\dots. \text{ and } m \neq N, 2N, 3N, \dots$$

For the three-element array, N=3, yielding,

$$\psi = \frac{2}{3}\, m\,\pi, \qquad m = 1,2,3,\dots. \text{ and } m \neq 3N \text{ or } 6$$

Therefore:

$$\delta = \frac{2}{3}\, m\,\pi - kd\, \sin\theta_i \cos\emptyset_i \qquad (6)$$

Consider now SA2 shown in Figure 2. The main advantage of this configuration is that the system can simultaneously perform beam steering towards the desired direction and nulling towards the interference direction. At the output of element A_1 is a digital beam steering weight "w_1" which must be set to maximize the beam towards the desired direction (e.g. base station). At the output of element A_3 is another weight "w_2" which will be used to create a null towards the interference direction (e.g. another base station or mobile station).

The electric field at the output of element A_1 and A_2 is:

$$E_{T1} = w_1 E_1 + E_2 \qquad (7)$$

The array factor of E_{T1} will be identical to that obtained for SA1. Hence:

$$AF_1 = 2\cos\frac{\psi}{2} \qquad (8)$$

where:
$\psi = kd_1 \sin\theta \cos\emptyset + \delta_1$ with $\delta_1 = -kd_1 \sin\theta_d \cos\emptyset_d$ (Maximize beam).

The electric field at the output of element A_2 and A_3 is:

$$E_{T2} = E_2 + w_2 E_3 \qquad (9)$$

The derivation of the array factor of E_{T2} will be similar to the derivation the array factor for SA1. Hence:

$$AF_2 = 2\cos\frac{\psi}{2} \qquad (10)$$

where:
$\psi = kd_2 \sin\theta \cos\emptyset + \delta_2$ and $\delta_2 = \pi - kd_2 \sin\theta_i \cos\emptyset_i$

(Minimize/Nulling the beam).

The total electric field and array factor of the system will be obtained from:

$$E_T = E_{T1} + E_{T2} \qquad (11)$$
$$AF = AF_1 \times AF_2 \qquad (12)$$

For this configuration, the system has more parameters in order to control the beam pattern. These parameters are δ_1, δ_2 and the spacing between the adjacent elements, d_1 and d_2. The distances of separation d_1 and d_2 are specified in terms wavelength λ. To achieve the optimum beam pattern, these parameters must be carefully designed. The different simulation results obtained by varying these parameters will be shown in the following section.

III. RESULTS AND DISCUSSION

The two three-element smart antennas (SA1 and SA2) array factor is given by:

$$AF = \frac{1}{3} \left| \frac{\sin\frac{3\psi}{2}}{\sin\frac{\psi}{2}} \right| \qquad (13)$$

where:
$\psi = kd \sin\theta + \delta$ with $\delta = \pm 2\, m\,\pi - kd \sin\theta_d$, where $k = \frac{2*\pi}{\lambda}$, $d = \frac{\lambda}{2}$, for m = 0,1,2, …, the beam is directed towards the desired direction (θ_d) and the results are as given in Figure 3 and Figure 4.
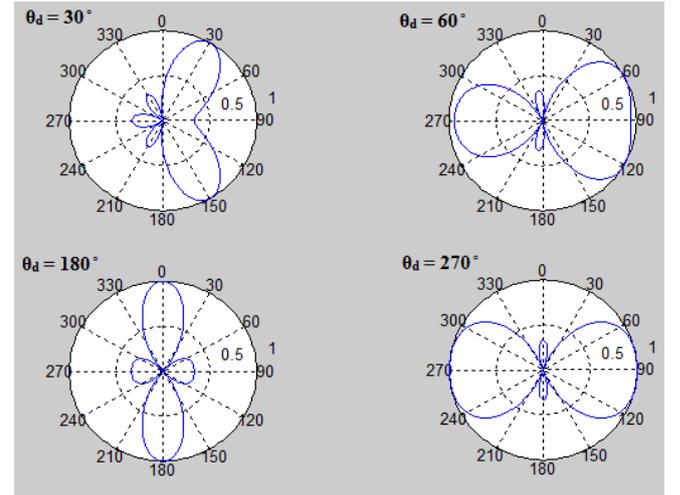

Figure 3: Maximizing the beam towards desired direction using SA1

When the desired direction is 30°, AF(30°) =1.0, which is good (Figure 3). But the reception from an interferer in the 60° direction, is half the maximum power of the interfering signal since the radiation AF is also more than half towards 60° (AF (60°) is about 0.5). With the SA1 configuration (Figure 1) of the three-element linear array, it is not possible to simultaneously maximize towards 30° and minimize (or null) towards 60°. Only one of the two options may be chosen; i.e. choose to maximize beam in one direction else choose to minimize beam in a direction. However, this is not the case with the three-element linear array antenna of SA2 configuration, where the two-weight adjusting signal processor units are positioned differently (Figure 2).

Consider now the three-element array antenna SA2 (Figure

2). Referring to the above equation (12): AF = AF$_1$ * AF$_2$ where:

$$AF_1 = cos\ \frac{\psi}{2}$$

where $\psi = kd_1\ sin\theta + \delta_1$ with $\delta_1 = -\ kd_1 sin\theta_d$ (Maximize beam), and:

$$AF_2 = cos\ \frac{\psi}{2}$$

where $\psi = kd_2\ sin\theta + \delta_2$ with $\delta_2 = \pi -\ kd_2\ sin\theta_i$ (Minimize/Nulling the beam) when $d_1 = \lambda/3$ and $d_2 = 2\lambda/3$, the results are shown is the following Figure 4.
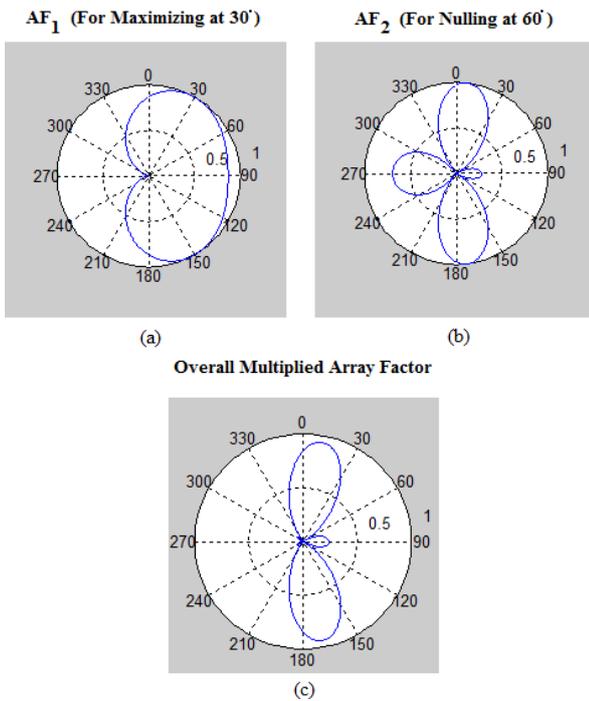

Figure 4: Simultaneous Maximizing and Minimizing the beam in two different directions using SA2. (a) Beam Maximizing at $\theta_d = 30°$, (b) Beam Nulling at $\theta_i = 60°$, (c) Average Beam with $\theta_d = 30°$ and $\theta_i = 60°$ [14]

Here it is possible to seek to maximize the beam in one direction as well as to minimize it in another direction simultaneously. Some imperfections are still seen to appear in that where we desire AF = 1 in the direction of 30°, it is a slightly reduced 0.75 that we obtain. However, the nulling in the 60° direction is perfect, as seen in Figure 4 (c). Therefore, by using three-element array antenna (configuration SA2), the system can do beam steering to the desired direction as well as to create null to the interference simultaneously with the proper choice of the distance of separation (d) values. The same comparison can be made with the three-element array antenna (configuration SA1).

IV. CONCLUSION

It has been shown that with the positioning of only two signal processing units in specific arms of the three-element array antenna system, as shown in Figure 2, it is possible to obtain an array antenna that may be used to simultaneously operate on two signals in the vicinity of the array antenna. It is also shown that if a different placement of the weighing signal processors is placed in different arms, it may not be possible to simultaneously operate on two signals in such a way as to maximize the reception of one signal and to null or cancel the reception of the other signal. Moreover, the technique presented in this paper has one further important advantage: the weights are obtained by simple algebraic operations without any need to resort to optimization numerical methods which consume time, battery power and digital memory. In a multi-element array smart antenna, where not all elements have a weight estimator behind them, as in the case of the three-element smart antenna presented herein, the positioning or placements of the weight estimators are of utmost importance.

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