An Electromagnetic Signal Processor for Beam-forming a Wireless Mobile Sensor Station: Strengthening the Desired Signal and Nulling Main Interference

P.R.P. Hoole[a], L.M. Abdul Rahim[b], Norhuzaimin Julai[c], Al-Hj Othman[d], Hikmah Shabani S.H.[e], Ade S W Marzuki[f], K.S. Senthilkumar[g], K. Pirapaharan[h], Aravind CV[i] and S.R.H. Hoole[j]

[a]*Corresponding author, Deparment of Electrical and Electronic Engineering, Universiti of Malaysia Sarawak, Sarawak, Malaysia. Email: prphoole@gmail.com*
[b]*Department of Electrical Engineering, University of Malaya, Kuala Lumpur, Malaysia*
[c-f]*Deparment of Electrical and Electronic Engineering, Universiti of Malaysia Sarawak, Sarawak, Malaysia*
[g]*Department of Computers and Technology, St. George's University, Grenada, WI*
[h]*Department of Electrical and Communications Engineering, Papua New Guinea University of Technology, Lae 411, PNG*
[i]*School of Engineering, Taylor's University, Malaysia*
[j]*Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, USA*

Abstract: This paper presents an electromagnetic signal processor of the electric field radiated by a three-element antenna array as a mobile station receiver which can increase power reception in the direction of the desired signal. As statistical, brute force estimation of the position of a wireless, mobile unit remains time consuming and memory wise heavy, as well as inaccurate, attempts are made to handle the changing environmental conditions surrounding a mobile unit, using estimators that function using more accurate, electromagnetic field models of the signal channel. Moreover, as reported in this paper, it is shown that analytically derived solutions of radiated electromagnetic fields may be used to increase the signal processing capability of the mobile unto to permit its transmission and reception maximized in a desired direction while cancelling out signals from undesired sources of interference. Number crunching systems consume time and memory, whereas the model based signal processor for beam steering proposed and investigated here is fast and light on memory usage. A two-element beam steered antenna presented before is extended to have a third antenna element placed in-between the two conventional elements, without any signal attenuation or phase shifting of this third element signal, results in a mobile unit that does simultaneous maximizing (towards the desired source) and minimizing (towards the undesired source or interferer) of the radiation signal strength.

*Keywords***:** Beam forming, Smart Antenna; Adaptive Array; Wireless mobile sensor.

1. INTRODUCTION

Antenna beam-forming, which is largely confined to stationary base station (BS) antennas, combines electromagnetic signals of array antenna elements to form a desired or expected output [1-3]. Signals in each element of the array antenna are multiplied by a complex weight and the output is formed by the receiver or the transmitter. The array antenna indeed acts like a space domain filter which suppresses signals arriving (or being transmitted) in certain directions, while amplifying signals from (or radiated from) certain angles. To maximize its performance the surroundings through which the signals will travel should be known. Beam forming is also called spatial filtering or spatial diversity combining [4].

To steer the beam of a mobile station antenna towards the base station, the phases of the weights are selected on-line to steer the main beam in the desired direction. In this paper we present a mobile station (MS) beamformer which simultaneously controls its direction of maximum radiation as well as the direction in which it should null outgoing or incoming electromagnetic signals, unlike previous work where such desired simultaneous signal processing was not possible. In previous papers we have reported on new developments using two element antennas [5], and three-element antennas where the maximizing of the beam in the desired direction and nulling the unwanted interferers had to be done *separately* and not *simultaneously* [6]. In this paper we report on a new structure for a three-element mobile station antenna, where despite the fact that the desired signal does not exactly fall on the maximum point of the electromagnetic beam, it falls within the 3-dB points of the beam while the beam simultaneously eliminates the interferer or reflected signal.

In mobile communication systems, a major problem facing the proper operation of line of sight (LOS) systems is multipath interference. The desired direct ray is usually interfered by reflected, diffracted or reflected/ diffracted rays causing fading and sometimes blockage. The direct ray is highly attenuated or blocked in many circumstances in mobile communication [7]. Multipath fading has a particularly deleterious effect because it causes deep fades in the signal amplitude that lead to decoding errors at the receiver. The effects of multipath are information data corruption, signal nulling, increasing or decreasing the signal amplitude. Therefore, multipath environment and null suppression of interference signal is one of the major challenges in mobile communication [4].

One major reason that multiple antenna elements on mobile handsets is prohibitive is the additional battery power needed for the signal processor [7, 8]. Although a two-element array antenna with only a single parameter estimation for beam forming is attractive, its limitations are significant [5]. We present in this paper an antenna radiation field equation based signal processor to make the mobile station antenna simultaneously increase reception of the desired signal (or increase radiation in the desired direction, when operating as transmitter) and cut off signals from interferers (e.g. other mobile users or reflected signals), or when acting as a MS transmitter, to minimize radiation in directions other than the direction of the receiver. This is the first time that a three-element array antenna is proposed for a mobile handset which simultaneously strengthens reception or transmission in the desired direction, while nulling the single interference signal. It is a promising technique that may be used to exploit the diversity principle used in MIMO's where at times the reflected signal (normally considered an interference) may be used as the main signal when the direct signal, for instance, may be cut down in strength due to shadowing created by buildings [9]. Moreover, such mobile station based beam steering may also be the best way to seek to compensate the negative effects of mobile station velocity [10].

2. THREE ELEMENT MOBILE STATION ANTENNA

The MS beam-forming processor makes use of estimation of the position of the MS (with respect to the BS) made by the position, or angle of arrival (AoA), estimator reported elsewhere [5, 11]. As soon as this information is

known, the processor of proposed array antenna system will do the weight calculation which will be used to beam steer the radiation pattern to the BS. The same process is repeated to do the nulling to the interference direction. The basic structure of the system is shown in Figure 1. The actions carried out by the electromagnetic signal processor are to use the received signal strength to estimate the two phase shifts to be imposed on the received signal before combining the two complex vectors with an unoperated third part (E_2) of the signal, as shown in Figure 2. One phase shift takes account of the AoA of the desired signal, and the other phase shift accounts for the AoA of the interference.
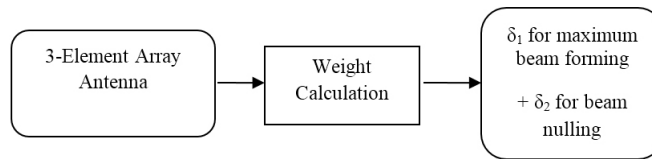

Figure 1: Structure of the antenna – Simultaneous maximizing and nulling using three element MS array antenna

The configuration of our three element array antenna is shown in Figure 2. The main advantage of this configuration is that the system can perform beam steering to the desired direction and nulling to the interference direction simultaneously. Simultaneous maximizing and nulling is a significant advantage, even as reflector-less single beam-beamforming is [12]. At the output of element A_1 is a digital beam steering weight w_1 (a complex vector) which must be set to maximize the beam towards the desired direction (e.g. towards the base station).
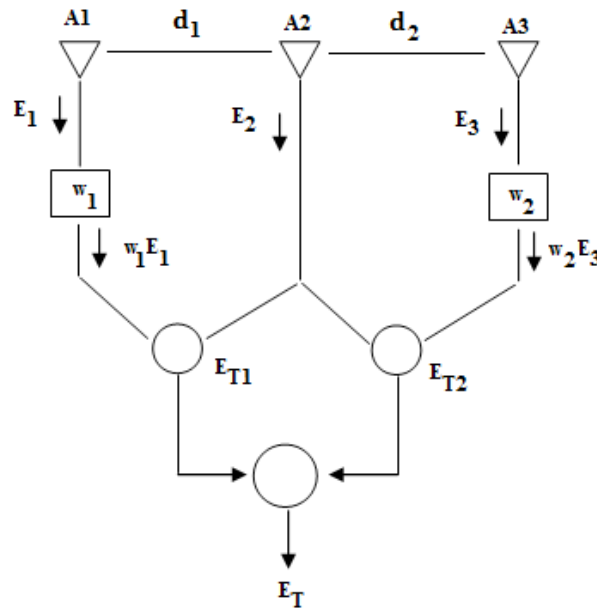

Figure 2: Signal processing configuration of three element array antenna

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 $E_{T1} = w_1E_1 + E_2$. The array factor of E_{T1} is given by [5, 11] Equation (1).

$$AF_1 = 2 \cos \frac{\psi}{2}, \text{ where } \psi = kd_1 \sin \theta \cos \varphi + \delta_1 \tag{1}$$

from which we obtain the first phase shift as in Equation (2)

$$\delta_1 = - kd_1 \sin \theta_d \cos \varphi_d \text{ (Maximize)} \tag{2}$$

The electric field at the output of elements A_2 and A_3 is $E_{T2} = E_2 + w_2 E_3$. Similarly, the array factor of E_{T2} and the associated phase shift are given by Equation (3)-(4)

$$AF_2 = 2 \cos \frac{\psi}{2}, \text{ where, } \psi = kd_2 \sin \theta \cos\varphi + \delta_2 \tag{3}$$

$$\delta_2 = \pi - kd_2 \sin \theta_i \cos \varphi_i \text{ (Minimize/Nulling)} \tag{4}$$

Therefore the total electric field and array factor of the system may be obtained from Equation (5)

$$E_T = E_{T1} + E_{T2} \tag{5}$$

Using the principle of pattern multiplication [13], we have Equation (6)

$$AF = AF_1 \times AF_2 \tag{6}$$

For the configuration of Figure 2, the system has four parameters which may be varied to control the beam pattern. These parameters are δ_1, δ_2 and the spacing between the adjacent elements, d_1 and d_2 in terms wavelength λ. The distances have to be intelligently chosen before fabrications, since once selected they may not be varied. The signal processor may however, control on line the two phase shifts to keep tuning the beams as the mobile station moves. To achieve the optimum beam pattern, these parameters must be carefully and considerably designed.

For the three-element array antenna, we may assume that the mobile station moves only along the ground and thus may be defined by the horizontal plane angle θ only, resulting in the following simplified expressions for array factors and phase shift angles as in Equation (7)- (10).

$$AF_1 = \cos \frac{\psi}{2}, \text{ where } \psi = kd_1 \sin \theta + \delta_1 \tag{7}$$

$$\delta_1 = -kd_1 \sin \theta_d \text{ (Maximize)} \tag{8}$$

$$AF_2 = \cos \frac{\psi}{2}, \text{ where } \psi = kd_2 \sin \theta + \delta_2 \tag{9}$$

$$\delta_2 = \pi - kd_2 \sin \theta_i \text{ (Minimize/Nulling)} \tag{10}$$

A complete three dimensional processor must take into account the vertical plane angle φ as well. We note that the estimation of the phase shift angles is completely defined, and does not need any numerical adaptive signal processor to estimate these angles for each position of the mobile station.

3. RESULTS AND SUMMARY

In Figure 3 are the simulation results for the three element antenna beams, which are identically equal to the resultant array factor [13] as in Equation (11).

$$AF = AF_1 \times AF_2 \tag{11}$$

when the individual radiation patterns of the elements may be set to be isotropic [5]. The resultant patterns are obtained for $d_1 = \lambda/3$ and $d_2 = 2\lambda/3$ (Figure 3(a)), and $d_1 = \lambda/2$ and $d_2 = \lambda/2$ (Figure 3(b)). Let us beam steer with the following parameters: desired signal angle of arrival AoA is $\theta_d = 40 \square$, the interference AoA is $\theta_i = 330 \square$.

From Figure 3 (a), the AF of the beam formed to direction $40\square°$ is not maximum (AF maximum $= 1$, the normalized array factor [5]), though strong (about AF $= 0.8$). However, Figure 3(a) shows that AF $= 0$ (null)

$$d_1 = \tfrac{\lambda}{3}, \; d_2 = \tfrac{2\lambda}{3} \qquad\qquad d_1 = \tfrac{\lambda}{2}, \; d_2 = \tfrac{\lambda}{2}$$
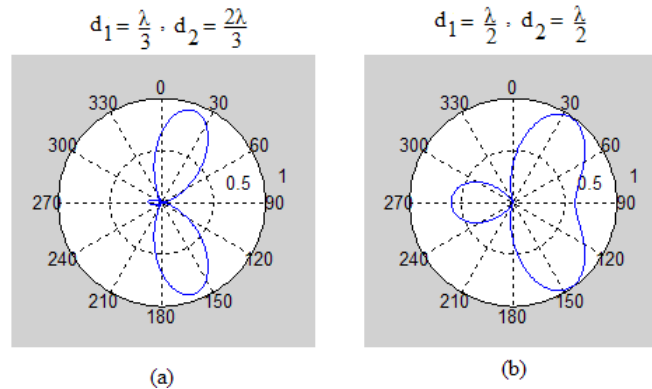

(a)   (b)

Figure 3: Beam forming and nulling with different "*d*" (three element array antenna of Figure 2)

towards the interference direction $\theta_i = 330\;\square$. From Figure 3(b) with different distances of separation, AF of the $40\square^\circ$ direction is maximum (AF = 1) and AF = 0 for the $330\square$ direction. However, the beam pattern is sharper in Figure 3(a) compared to Figure 3(b), which means that radiation in unwanted directions is confined to a narrow region. These differences are due to the different distances of separation between the three elements.

Consider the difference between a two-element antenna and the three element antenna configuration (Figure 2) proposed in this paper. This comparison will illustrate some important features and limitations of the three element antenna. It is desired that the beam is directed to $\theta_d = 30\square$ and simultaneously nulled at $\theta_i = 60\;\square$. Using *s* two-element array antenna [2], the antenna array factor is maximized at $30\square$. This is shown in Figure 4. However, signal processing of the received signals, it is not possible to simultaneously null the interfering signal at $60\;\square$.

Although the beam is maximized towards the desired signal at $30\square$, as seen in Figure 4, the interfering signal at $60\square$ also gets into the receiver almost at the strength at which it arrives at the two-element receiver antenna.
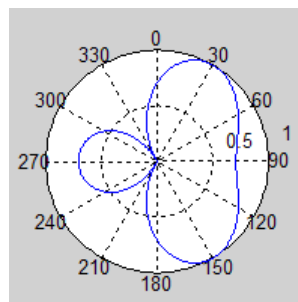

Figure 4: Two element array antenna beamforming to $\theta_d = 30\;\Omega$ [2]

Consider now the case for the three-element array of Figure 2, with $d_1 = \lambda/3$ and $d_2 = 2\lambda/3$, The two array factors AF_1 and AF_2 of equations (7) and (9) respectively are as shown in Figs. 5(a) and (b). We can see that AF_1 helps to maximize the desired signal at $30\square$ and AF_2 helps to null the signal at $60\;\square$. When the resultant array fact AF is obtained from equation (11), the three element antenna is seen to seek to simultaneously maximize the desired signal received and to null the interfering signal. However, the multiplying of the two array factors to get the resultant array factor slightly degrades the maximizing effect in the $30\square$ direction. Therefore, by using three-element array antenna (configuration 2), 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 "*d*" values. The same comparison can be made with the three-element array antenna (configuration 1). The three element array antenna shown

in Figure 2 allows for simultaneous suppression of interference or unwanted signal, while steering the beam to receive or transmit signals in the desired direction. The electromagnetic signal processor presented here needs no brute force computation to beam form, since it depends on an analytical solution for the resultant array factor of the three element electric field of a three element antenna. The distances of separation between the two elements have a modifying effect primarily on the pointing angle of the beam maxima in relation to the AoA of the desired signal.
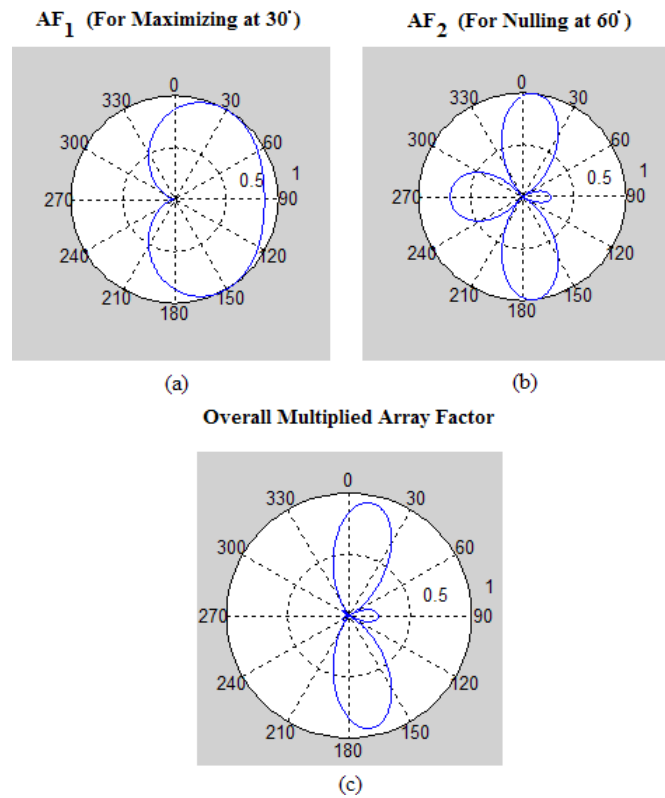

Figure 5: Three element array antenna (a) beam maximizing at $\theta_d = 30^\circ$ (b) beam nulling at $\theta_i = 60^\circ$ (c) average beam with $\theta_d = 30^\circ$ and $\theta_i = 60^\circ$

Acknowledgement

REFERENCES

[1]   S. Chen, S. Sun, Q. Gao and X. Su, "Adaptive Beamforming in TDD-Based Mobile Communication Systems: State of the Art and 5G Research Directions", IEEE, Wireless Communications, Dec 2014, pp. 81-87.

[2]   P.R.P. Hoole, "Smart Antennas for communication, medical and radar systems", WIT Press, UK, 2001.

[3]   M. Agrawal, A. Roy and N. Saxena, "Next Generation 5G Wireless Networks: A Comprehensive Survey", IEEE Communications Survey and Tutorials, vol. 18, 3, 2016, pp. 1617-1675.

[4]   Ivica Stevanovic, Anja Skrivervik and Juan R. Mosig, "Smart Antenna Systems for Mobile

[5]   Communication", Final report, Laboratoire d'Électromagnétisme et d'Acoustique, École Polytechnique Fédérale de Lausanne, January 2003, pp. 10-23, 73.

[6]   P.R.P. Hoole, K. Pirapaharan and S. R. H. Hoole, "An Electromagnetic Field Based Signal Processor for Mobile Communication Position-Velocity Estimation and Digital Beam-forming: An Overview," *Int. J. of Applied Electromagnetics and Mechanics*, Nov. 2011.

[7]   K.S. Senthilkumar, K.S., K.Pirapaharan, G.A.Lakshmanan, P.R.P Hoole, S.R.H. Hoole, "Accuracy of Perceptron Based Beamforming for Embedded Smart and MIMO Antennas", Proc. International Symposium on Fundamentals of Engineering, IEEE Xplore Digital Library, Pages: 1 - 6, DOI: 10.1109/ISFEE.2016.7803215, Jan 2017,

[8]   D. Muirhead, M. A. Imran and K. Arshad, "Survey of the Challenges, Opportunities and Use of Multiple Antennas in Current and Future 5G Small Cell Base Stations", IEEE Access, Vol. 4, 2016, pp. 2962-2964.

[9]   W. Geyi, Q. Rao, S. Ali and D. Wang, "Handset Antenna Design: Practice and Theory", Progress in Electromagnetics Research, PIER 80, 123-160, 2008, pp.124 -127.

[10]   John L. Volakis (2007), "Antenna Engineering Handbook", 4th Edition, Chapter 36: Mobile Handset Antennas, Mc Graw Hill, 2007.

[11]   Michael J. Chu, "Effect of Mobile Velocity on Communications in Fading Channels", IEEE Trans on Vehicular technology," Vol. 49, No. 1, Jan 2000.

[12]   Wang, X., P. R. P. Hoole, and E. Gunawan, "An electromagnetic-time delay method for determining the positions and velocities of mobile stations in a GSM network" , J A Kong (Editor), Progress In Electromagnetics Research, Vol. 23, 165-186, 1999.

[13]   K. Pirapaharan., Herman Kunsei, K.S. Senthilkumar, P.R.P Hoole, S.R.H. Hoole, "A Single Beam Smart Antenna for Wireless Communication in Highly Reflective and Narrow Environment", Proc. International Symposium on Fundamentals of Engineering, IEEE Xplore Digital Library. Pages: 1 - 5, DOI: 10.1109/ISFEE.2016.7803214, 2017

[14]   P.R.P. Hoole, K.Pirapaharan. Hoole and S.R.H. Hoole, "Engineering Electromagnetics Handbook", WIT Press, UK, 2013