An Electromagnetic Field Based Signal Processor for Mobile Communication Position-Velocity Estimation and Digital Beam-forming: An Overview

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A central issue in increasing mobile communication system capacity, coverage and data rate is the development of a fast, reliable algorithm to narrow and steer the adaptive antenna beam towards the mobile stations (MS). In this and other central areas faced, the use of electromagnetic signal processing is key in seeking narrower, rapidly manoeuvrable antenna beams carrying higher data rates. To locate the MS and to beam steer, we present here an overview of a novel electromagnetic field based signal processor as an alternative to the currently popular direction of arrival (DOA) algorithms. Our algorithm allows for simultaneous position-velocity estimation and digital antenna beam-steering. Using the integral solution of the radiated far fields, the MS radiated power measured at three base stations (BS) and a maximum likelihood estimator (MLE) are used to operate on the analytical solution of the radiated field to obtain the location of the MS and the instant by instant steering of the two-element MS antenna beam. The widely used mobile communication time-delay method is modified by antenna radiation pattern data to provide a new electromagnetic time delay method which provides the first estimate to start up the new position-velocity estimation and digital beam-forming weights of the array MS.

Key Words: Smart antennas, Mobile communications, Applied electromagnetism, Mobile phone location, Direction finding, Software solution.

1. Introduction

The search for effective smart antennas is of major interest to i) increase the effectiveness of the use of the crowded frequency spectrum, ii) increase the amount of data or users that a system can handle, iii) reduce the load on the battery and iv) increase the coverage range of the Base Station (BS) [1]. In addition, the effort to cut down hardware and borders associated with each BS in *ad hoc* systems where the BS's functions will be taken over by Mobile Stations (MSs), requires effective beam steering at the MS, such as small hand held telephone units. We present here an algorithm that not only uses the mobile communication electromagnetic waves to determine the position of the MS, but also, simultaneously to form the antenna beam so as to steer it and narrow it towards the BS that is handling it.

The need to perform high resolution location of the MS (e.g. hand phone) is there in order to digitally steer the MS array antenna beam towards the BS handling that particular MS, and to cut off the interference (null) from other MSs [2-6]. Indeed the three dimensional position of the MS is needed in the more complex situation where the MS is moving up or down in a high rise building, or it is in a vehicle such as a helicopter with changing positions in all coordinates (x, y and z). In this paper, however, we assume movement in the two dimensions (x, y) only and assume that the vertical height or position of the MS (z) remains constant [7-13]. We present in this paper a very different approach to not only determine the position-velocity of the MS, but also to control simultaneously the beam of the smart antenna using an electromagnetic radiation field based signal processor that determines the spatial location of the MS, as well as to determine the weights that need to be imposed on the signals transmitted or received by the array antenna transceiver (transmitter/receiver) in order to keep the antenna beam steered towards the nearest BS[14].

We explore a different route to getting the DOA: using our knowledge of the electric field strength at the receiving BS antenna, we operate on the electric field strengths of the signals received at three different BSs to estimate the position and velocity of the MS [15, 16]. We have explored the possibility of developing a mobile communication antenna signal processor that uses much of the information the system inherently possesses of the types of antennas used in BSs and MSs. This has opened up a vast number of possibilities which require intensive and applied investigations into the greater use of the electromagnetics of array antenna engineering. We deal here with the linearly polarized antenna beams,

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as opposed to the circularly polarized beams when satellites are involved [5]. Although the current research work in mobile communication antennas is focused on statistical and geometric ray theory approaches, future (fourth or fifth generation mobile systems) will require the use of electromagnetic theory, including low orbit satellites to communicate directly with an MS, rapidly moving vehicle-to-vehicle communications with data rates going up to 50 MB/s, and multi-element MS antennas.

2. The Wireless, Mobile Communication System

In Fig. 1 is shown the wireless, mobile communication scenario this paper addresses. A fast moving automobile is the MS. It moves from cell to cell at varying speeds. As it so moves, it communicates with the stationary tower based base station (BS) within the cell. Once it moves into the next cell, it is handed off to the BS in the cell of its movements. But as it moves within one cell, we assume that its signal is strong enough to be received and detected by BSs other than the BS with which it communicates. The field strengths picked up by adjacent cells will be used to determine the position of the MS.

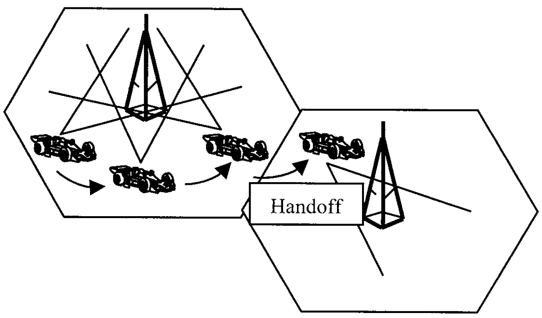


Fig. 1 The cellular wireless, mobile communication.

Assuming a digitally steerable MS antenna beam, we consider a two-element, dipole wire MS antenna. This will need to be a future necessity, although not presently developed for or implemented in second or third generation mobile communication systems.

In Fig. 2 the is shown the test route of the MS over which the electromagnetic signal processor for position estimation and beam forming for communicating with the base station is tested. In Fig. 3 the speeds of the MS (in km/hr) are indicated; the speeds indicated by 1, 2, 3, ... 9 in Fig. 3 correspond to points 1, 2, 3, ..., 9 shown in Fig. 2.

Moreover, Table 1 shows the basic MS antenna parameters used in this simulated system. Two types of cells are considered: the 2000 m separation between adjacent BSs, the M (Medium)-cells with the demand for increased transmitter power (10 W), and the smaller 250 m separation between adjacent BSs, the P (Pico)-cells demanding less transmitter power (e.g 0.1 W).

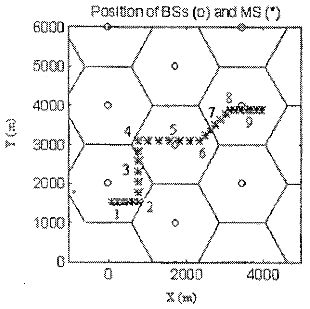


Fig. 2 The Route of the MS in the x-y plane.

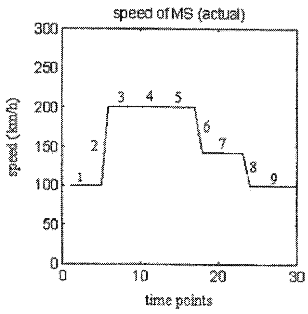


Fig. 3 The Changing Speeds of the MS.

Table 1 Parameters of the Mobile Communication Systems on which the performances of the mobile-phone locating algorithm (focus of this paper) and the smart antenna beam steering algorithm are tested out.

Parameters	Description
$f = 900$ MHz	Signal frequency in GSM system
$c = 3\times10^8$ m/s	Speed of light
$z_1 = 60$ m	Height of the lower part of the BS antenna
$z_2 = z_1 + \lambda/2$	Height of the upper part of the BS antenna
$z_j = 1$ m	Height of the MS antenna
$R_r = 73\ \Omega$	Radiation resistance of the BS antenna
$P = 10$ W (M-cells)	Radiation power of the BS antenna
$P = 0.1$ W (P-cells)	

3. Beam-forming with Position and Velocity Estimator (BFPVE)

A single module that performs beam-forming and position-velocity estimation simultaneously in each iteration process is proposed. The module is based on position and velocity estimators developed by various authors [17-21], and used for the electromagnetic position-velocity estimator [22]. The latter is further developed to yield a simultaneous beam-forming, or antenna weighting algorithm. Assuming that the antenna is a finite-sized dipole, its radiated electric field is given by [15]

$$E(r,z) = A_0\left[\frac{z_j - z_1}{\sqrt{r^2 + \left(z_j - z_1\right)^2}} - \frac{z_j - z_2}{\sqrt{r^2 + \left(z_j - z_2\right)^2}}\right] \quad (1)$$

where

$$A_0 = \frac{\mu_0 \omega I_0}{4\pi} = 10^{-7}\omega I_0 \quad (2)$$

and

$$I_0 = \sqrt{\frac{P_{\rm rad}}{R_{\rm rad}}} \quad (3)$$

where P_{rad} is the radiation power received at the BS, and R_{rad} is the radiation resistance of the BS antenna. The larger BS antenna has a lower end height of z_1 and upper end height of z_2, and the MS is at a horizontal distance r from the BS, and at a height z_j from ground when the MS is at any point j in the vertical spatial domain. From the measured power at the BS, we seek to determine the distance r from three BSs in order to locate the MS to beam steer the BS antenna. The MLE was used to perform according to this estimation [14].

The measured instantaneous electric field strengths E_m in the presence of Additive White Gaussian (AWG) noise is modelled by [23]

$$E_m = E + n, \tag{4}$$

where E is a function of r as seen in Eq. (1).

First, an initial estimated r and the weight w applied to one of the two elements of the antenna are assumed to be obtainable (described in Section 4). From this assumption, E can be made a function of only one of the two parameters (r and w). Thus an estimator for r and w can be derived.

$$r^{n+1} = r^n + \left(Jr_n^T Jr_n\right)^{-1} Jr_n^T \left(E_m - E_n\right), \tag{5}$$

where J_n is replaced by J_{rn}, and

$$w^{n+1} = w^n + \left(Jw_n^T Jw_n\right)^{-1} Jw_n^T \left(E_m - E_n\right), \tag{6}$$

4. Electromagnetic Time-delay Method (ETDM) for Mobile Stations

The least mean square (LMS) method [24] is used to get $\boldsymbol{r}$. The electric field strength $\boldsymbol{E}(\boldsymbol{r})$ at a distance $\boldsymbol{r}$ from the MS is given by Eq. (1), and it may be cast in the form,

$$\boldsymbol{E}(\boldsymbol{r}) - \boldsymbol{E}(\boldsymbol{r}_0) + \frac{\partial \boldsymbol{E}}{\partial \boldsymbol{r}}\Delta \boldsymbol{r} + \boldsymbol{0}(\Delta \boldsymbol{r}) - \boldsymbol{E}_0 + J_0 \Delta \boldsymbol{r} + \boldsymbol{0}(\Delta \boldsymbol{r}) \tag{7}$$

where $\boldsymbol{0}(\Delta r)$ can be ignored when Δr is very small compared with $\boldsymbol{r}$ and

$$\boldsymbol{J}_0 = \begin{bmatrix} \partial E_1/\partial r_1 & & 0 \\ & \partial E_2/\partial r_2 & \\ 0 & & \partial E_3/\partial r_3 \end{bmatrix} \tag{8}$$

The error between measurement and the theoretical value for the electric field strength is given by

$$\varepsilon = \boldsymbol{E}_m - \boldsymbol{E}(\boldsymbol{r}) = (\boldsymbol{E}_m - \boldsymbol{E}_0) - \boldsymbol{J}_0 \Delta \boldsymbol{r} \tag{9}$$

Minimizing ε^2 we get

$$\boldsymbol{r}^{k+1} = \boldsymbol{r}^k + \left(\boldsymbol{J}_k^T \boldsymbol{J}_k\right)^{-1} \boldsymbol{J}_k^T \left(\boldsymbol{E}_m - \boldsymbol{E}^k\right) \qquad k = 1,2,3\ldots \tag{10}$$

The distance from the MS to each of the BTSs is obtained from Eq. (10). However, the goal is not to get $\boldsymbol{r}$, but the position of MS, i.e., to get $\boldsymbol{PM}$. We use the LMS method again to obtain $\boldsymbol{PM}$ from $\boldsymbol{r}$. The main iteration equation to get the $\boldsymbol{PM}$ from $\boldsymbol{r}$ resembles Eq. (10) and is given by,

$$\boldsymbol{PM}^{k+1} = \boldsymbol{PM}^k + \left(\boldsymbol{J}_k^T \boldsymbol{J}_k\right)^{-1} \boldsymbol{J}_k^T \left(\boldsymbol{0} - Errp_k\right) \tag{11}$$

where

$$Errp = \left|\boldsymbol{PM} - \boldsymbol{PB}\right| - \boldsymbol{r} \tag{12}$$

$\boldsymbol{J}_k$ is redefined as

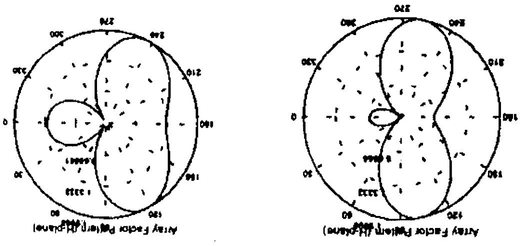
$$\boldsymbol{J}_k = \begin{bmatrix} \partial Errp_1/\partial x & \partial Eeep_1/\partial y \\ \partial Errp_2/\partial x & \partial Eeep_2/\partial y \\ \partial Errp_3/\partial x & \partial Eeep_3/\partial y \end{bmatrix} \tag{13}$$

Although the accuracy of the $\boldsymbol{r}$ and $\boldsymbol{PM}$ estimations obtained by using ETDM is poor, it was found to be a useful method to obtain the initial value for FSM.

5. Simulation Results and Discussion

Using the MS positions estimated by the position estimator Eq. (11), a MS two-element antenna beam is steered using Eq. (12).

In Fig. 4 is shown the radiation pattern of the two element MS antenna when the MS is travelling at about 200 km/hr in segment 5 of its route profile when the BS transceiver (BST) is at (2000m, 3000m) for that segment. Over the entire route, it was seen that the two element antenna could be digitially steered and focused towards the desired signal to/from the nearest BST.



(a) (b)

Fig. 4 Digitially steered MS Antenna Beams when the BS is at (a) – 60^0 and (b) – 76^0.

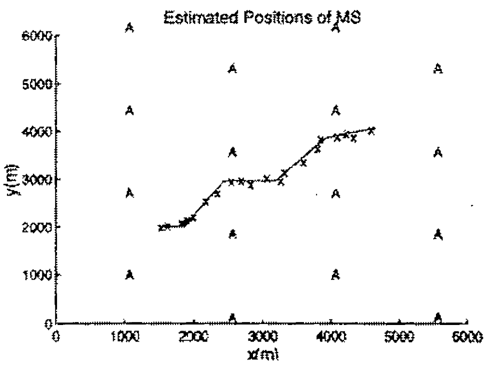


Fig. 5 Estimated positions of the MS.

In Fig. 5 is shown the estimated positions of the MS as it moves through the communication cells serviced by a BS. The actual path taken by the MS is shown by a hard line, and the estimated positions of the MS are shown by asterixes (*). The BSs are shown by the letter "A" in Fig. 5.

6. **Conclusions.**

This paper has reported the novel, and successful use of the electromagnetic radiation pattern of a mobile communication array antenna to beam-form a two-element MS antenna to improve the performance of the system. The signal processor based on the radiation pattern of the antenna is able to determine simultaneously the position (and velocity) of the MS, as well as steer the beam (through weighted beaming) towards the nearest BS. The directivity, coverage, effective use of the frequency bandwidth and system capacity may be improved using such a smart antenna on the MS. The possibilities opened up by this new approach of using the knowledge we have of the spatial-temporal characteristics of an antenna for technological innovation, are vast and many. Although this work is still in its preliminary stages, the development of effective electromagnetic signal processors for smart antennas can significantly contribute to the solution of problems related to present and future wireless, mobile communications systems.

References

[1] G. V. Soulos, *Adaptive Antennas for Wireless Communications*, IEEE Press, 2001.

[2] A. J. Paulraj and C. B. Papadias, "A space-time processing for wireless communications," *IEEE Signal Processing Magazine,* Vol. 14, No. 6, pp. 49-83, 1997.

[3] S. Glisic, *Advanced Wireless Communications*, John Wiley, New York, 2004.

[4] R. O. Schmidt, "Multiple emitter location and signal parameter estimation," *IEEE Trans. Antenna Propag*., Vol. 34, No. 3, pp. 276-280, 1986.

[5] R. Scholtz, "Frame Synchronization Techniques," *IEEE Trans. Communications,* Vol. 28, No. 8, pp. 1204-1213, 1980.

[6] B. Friedlander, "A Passive localization algorithm and its accurate analysis," *IEEE Journal of Oceanic Engineering*, Vol. OE-12, No. 1, pp. 234-244. 1987.

[7] J. Li, "Computationally efficient angle estimation for signals with known waveforms," *IEEE Trans. Signal processing*, Vol. 43, No. 9, pp. 2154-2163, 1995.

[8] P. Stoica, and A. Nehorai, "MUSIC, Maximum likelihood and Cramer-Rao bound," *Proc. IEEE* , Vol. 57, No. 8, pp. 1408-1418, 1969.

[9] Y. I. Chan and K C Ho, "A simple and efficient estimator for hyperbolic location," *IEEE Trans. Signal processing*, Vol. 42, No. 8, pp. 1905-1915, 1994.

[10] W. H. Foy, "Position-location estimation," *IEEE Trans. Aerospace and Electronic Systems*, Vol. AES-12, No. 2, pp. 187-193, 1976.

[11] J. S. Abel and J. G. Smith, "Source range and depth estimation from multiple range difference measurement," *IEEE Trans. Acoustics, Speech and Signal processing*, Vol. 37, No. 8, pp. 1157-1165, 1989.

[12] R. O. Schmidt, "Multiple emitter location and signal parameter estimation," *IEEE Trans. Antennas and Propagation*, Vol. AP-34, No. 3, pp. 27-80. 1996.

[13] D. J. Torrieri, "Statistical theory of passive location systems," *IEEE Trans. Aerospace and Electronic Systems*, Vol. AES- 20, No. 2, pp. 183-198, 1984.

[14] P .R .P. Hoole, "Smart Antennas and Signal," *Processing in Telecommunication, Biomedical and Radar Systems*, WIT Press, UK, 2001.

[15] P. R. P. Hoole and S R H Hoole, "Computing Transient Electromagnetic fields," *J Applied Physics,* Vol. 61, pp. 3473 -3476, 1987.

[16] S. R. H. Hoole and P. R. P. Hoole, *A Modern Short Course in Engineering Electromagnetics,* Oxford University Press, New York, 1996.

[17] M. Hellebrandt, R. Mathar and M. Scheidenbogen, "Estimating position and velocity of mobiles in a cellular radio network," *IEEE Trans. Vehicular Tech.,* Vol. 46, No. 1, pp. 65-71, 1997.

[18] M. Pent, M. A. Spirto and E. Turco, "Method for positioning GSM mobile stations absolute time delay measurements," *IEE Electronics Letters,* Vol. 33, No. 24, pp. 2019-2020, 1997.

[19] M. Hata and T. Nagatsu, "Mobile location using signal strength measurements in a cellular system," *IEEE Trans. Vehicular Tech.,* Vol. VT-29, pp. 245-252, 1980.

[20] K. Kawabata, T. Nakamura and E. Fukuda, "Estimating velocity using diversity reception," *Proc. IEEE 44th Veh. Tech. Conf.,* Stockholm, pp. 371-374, 1994.

[21] S. Riter and J. McCoy, "Automatic vehicle location-An overview," *IEEE Trans. Vehicular Tech.,* Vol. VT-26, pp. 7-11, 1997.

[22] X. Wang, P R P Hoole and E. Gunawan, "An electromagnetic time delay method for determining the positions and velocities of mobile stations in GSM network," *Progress in Electromagn. Res.*, Vol. PIER-23, pp. 165-186, 1999.

[23] C. Look and N. Second, "Computer model for fading channel with application to digital transmission," *IEEE Trans. Vehicular Tech.,* Vol. 40, No. 4, pp. 700-707, 1991.

[24] B. Widdrow and S D Stearns, *Adaptive Signal Processing, Prentice-Hall*, 1985.