

Base-Station Tracking in Mobile Communications Using a Switched Parasitic Antenna Array

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Abstract—Base-station tracking in mobile communications benefits from a directional antenna and so requires direction finding technology. A novel technique for electronically directing the radiation pattern of an antenna array employs a directional array with only one active element and three parasitic elements operating near resonance. Three different methods of direction finding are assessed; a coarse angular location method, a precise angular location method assuming one incident beam, and a precise angular location method with multiple incident beams. An array with n elements, if used in conjunction with a relatively simple controller, can be used to resolve $n - 1$ signals. This technology can be implemented using both wire and patch antenna-array elements and either linear or circular polarization can be used, lending the technology to applications in both terrestrial and satellite communications systems.

Index Terms—Antenna arrays, mobile communication.

I. INTRODUCTION

IN digital communications systems, it is possible to have a periodic break in the transmission of information without degrading the signal transmitted. This break in transmission can be used to optimize the communications channel. One factor that can greatly improve the channel is the use of a directional antenna system. In this paper, we propose that in between data segments, the mobile transceiver maintains the optimal channel by re-orienting the antenna system. This is only possible if the time required to perform the operation is sufficiently small and the directivity of the antenna is adequate. We suggest that an electronically steerable switched parasitic antenna array supported by a small digital controller can achieve these objectives, even in severe multipath environments. The solutions we suggest are evaluated in the context of time-domain multiple access (TDMA) in group special mobile (GSM) mobile telephone communications for use in base-station tracking but are far more generally applicable.

When using directional antennas, intelligent high-speed direction-finding techniques are required and, in the case of a mobile transceiver, the system must have low-power requirements. With conventional directional antenna systems

for initial signal acquisition and subsequent direction updates, a full 360° scan may be required. We propose a technique that will enable the updates to be minimized and allow the direction to be determined without a full 360° scan periodically. Current direction-finding techniques include conical scan, sequential lobing monopulse, and track-while scan [1], [2]. These techniques require the use of either mechanically rotating antennas, crossed loops or phased arrays.

In direction finding, multiple incoming signals can result in an incorrect angular position being determined. A common method used to resolve multipath and/or multiple signals is the use of high-gain narrow-beam mechanically rotating antennas [1], [2]. This method can resolve two or more signals provided they are separated by an angle greater than the beamwidth of the antenna. Thus, the number of signals that can be detected depends on the beamwidth of the antenna. Other techniques for minimizing the impact of multipath interference involve the implementation of frequency hopping, polarization agility, and space diversity. A previous paper discusses the use of four directional arrays to reduce the fading caused by multipath signals [3]. This technique uses four separate arrays, each with a directional pattern, and requires switching between these arrays.

The methods used to reduce the effects of multipath mentioned above have been successful, however, these systems are generally quite complex. Where possible, it is desirable to avoid mechanically rotating parts so that power consumption is kept to a minimum. The alternate methods have involved the use of phased arrays, allowing 360° rotation with no moving parts. This would seem an ideal solution, however, in order to track multipath signals, a full 360° sweep is required regularly so that the desired signal is distinguished from other spurious signals. This process is time consuming with both the phased array and the mechanically steerable arrays and with phased arrays it is also computationally intensive. Certain applications cannot afford the time spent in these cases, for example, with the TDMA modulation scheme used in GSM for mobile telephones, the minimum interval between frames is 4.038 ms.

II. ELECTRONICALLY STEERABLE ANTENNA ARRAY

The basic concept of an electrically steerable switched-parasitic antenna array has been presented previously [4], [5]. Near-resonance parasitic elements are used to create a directional electronically steerable antenna array. This technique can be applied to both wire antenna structures (e.g.,

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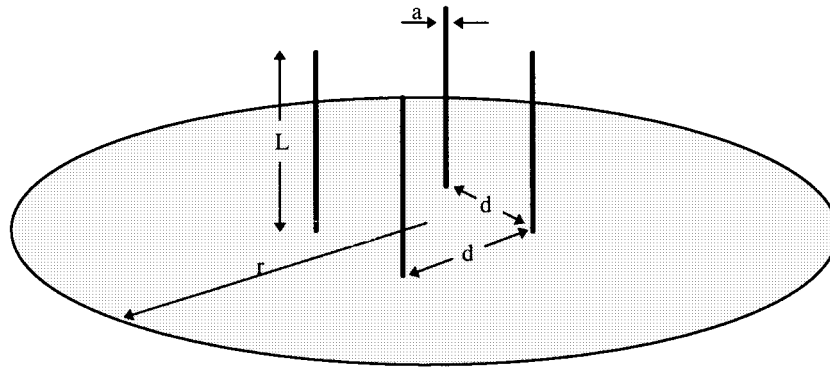


Fig. 1. A four-element monopole switched-parasitic antenna array $d = 0.27\lambda$, $L = 0.25\lambda$, $r = 0.625\lambda$, and wire radius $a = 0.005\lambda$.

dipole or monopole elements) and patch arrays. In this paper, applications using a four-element monopole array operating at 1.5 GHz are discussed. The antenna array consists of one active element and three parasitic elements operating near resonance. The structure is shown in Fig. 1, giving all dimensions and the theoretical radiation pattern found; using NEC2 for all four directions is shown in Fig. 2. Electronic steering of the beam is achieved by switching the feed position between the four elements using a single-pole four-throw RF switch and then switching the parasitic elements in or out of resonance using appropriately biased RF *p-i-n* diodes.

III. DIRECTION FINDING

The switched-parasitic antenna array described in the previous section has been proposed for use in a direction-finding system for the tracking of base stations in mobile communications. This system provides a simple direction-finding solution to both single- and multiple-signal detection. The array can be used in three different modes:

- Mode 1* coarse angular location of a single source;
- Mode 2* precise angular location of a single source;
- Mode 3* precise angular location of multiple sources.

Modes 1 and 2 have been presented previously [6]. In all three cases, the primary input information is the total signal strength measured at each of the four switch positions and a knowledge of the 360° radiation pattern of the array.

A. Mode 1

This technique tracks a source and electronically orients the beam of the antenna in such a way as to always be receiving the maximum incident signal regardless of the position of the receiver. For a single source and when precise determination of the angular location is not required, this technique provides a simple solution with low acquisition time.

Using the four-element parasitic array described previously, with the four patterns shown in Fig. 2, the field strength at each of the four positions q_1 , q_2 , q_3 , and q_4 is detected sequentially. The maximum value is determined and the antenna is switched to the position that gives the maximum signal until a further update is required. The time taken to perform this operation is primarily limited by the speed of the analog-to-digital converter (ADC) of the controller. For example, a likely time

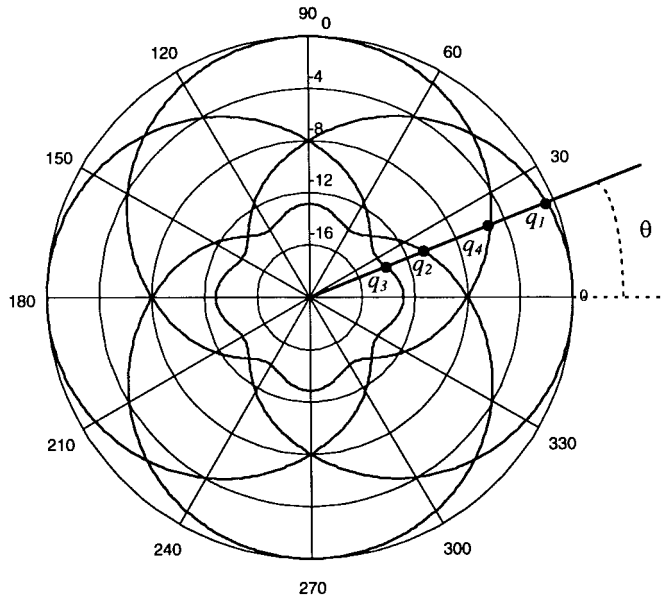


Fig. 2. Radiation pattern of four-element monopole array shown in Fig. 1 for all four switch positions with a single active antenna element calculated using NEC2.

would be 100 μ s using a standard MC68HC11 with 2-MHz clock. This method is similar to the four-array system used to minimize multipath fading [4].

When operating in this mode, it is necessary to constantly repeat the process of signal tracking, as it is not known in which section of the quadrant the signal lies.

B. Mode 2

This mode of operation also requires the signal strengths q_1 , q_2 , q_3 , and q_4 at each of the four switch positions to be detected. The angular location can then be determined within 45° by the order and relative magnitudes of the four received strengths. For example, if $q_1 > q_2$, q_3 , and q_4 , then it is known that the signal lies in the quadrant q_1 . Then, if $q_4 > q_2$ and q_3 , it is also known that the signal lies in the half of quadrant q_1 closest to quadrant q_4 . This is demonstrated graphically in Fig. 2. A more precise determination of the angle is then found by comparing the differences between the signals, i.e., $q_1 - q_2$, $q_1 - q_3$, $q_1 - q_4$, etc. with the radiation pattern and finding the angles on the radiation pattern that

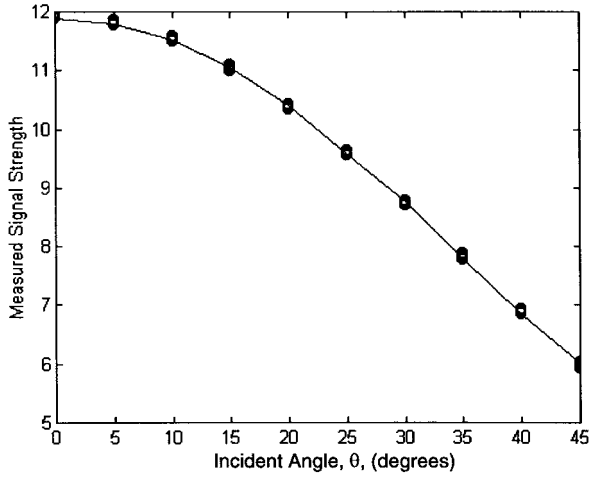


Fig. 3. Angle determination results in the presence of -20 dB noise for a single incident signal.

correspond to these differences. It should be noted that due to the determination of the angle within a 45° section first and due to the symmetry of the radiation pattern, it is only necessary to store half of the radiation pattern. With no noise present, this method provides an exact solution. The presence of noise will introduce some error into the angle determination, the extent of which is demonstrated graphically in Fig. 3. To obtain this information, the system was modeled using MATLAB and the random function was used to add normally distributed random noise to the incident signal. In this figure, noise of -20 dB has been added, introducing an error of less than 5° . It is only necessary to show one half of a quadrant as the other half will be identical.

The time required for this mode is simply that required by the Mode 1 controller to access a look-up table. This is estimated to result in a total update scan time of less than $200 \mu\text{s}$.

When operating in this mode, it is possible to predict the movement of a source in relation to the receiver by knowing the previous measurements. Therefore, it will not be necessary to perform full 360° measurements as it is extremely unlikely that the source will move through more than a 90° sector within the time between measurements. Once the angular position of the source has been initially determined, a dither algorithm will then be sufficient to continue tracking. This will shorten the time required for each measurement.

This algorithm will not provide a solution if there are multiple signals within the same quadrant. If the signal with maximum strength lies in a different quadrant to the multipath signals then it is possible to track the desired signal with small error.

C. Mode 3

This section of the paper concentrates on resolving two signals only, for example, a desired plus a multipath signal. If required, however, the technique can be extended to resolve three signals with the four-element array or more than this with the addition of more symmetrically positioned elements and slightly more processing.

As with modes 1 and 2, the array is switched between the four orthogonal positions sequentially and the total signal at each position q_1 , q_2 , q_3 , and q_4 is detected. From this information, the object is to determine m_1 and m_2 , the strengths of the two incoming signals, and θ_1 and θ_2 , the angular positions of the two incoming signals.

The total measured signal strength for the first switch position q_1 can be written

$$q_1 = m_1 G(\theta_1) + m_2 G(\theta_2) \quad (1)$$

where $G(\theta_1)$ and $G(\theta_2)$ are the antenna gains at θ_1 and θ_2 for patterns one and two, respectively.

At the next position, 90° away from the first position, the new signal strength q_2 would be

$$q_2 = m_1 G(90 + \theta_1) + m_2 G(90 + \theta_2). \quad (2)$$

Similarly, we can write

$$q_3 = m_1 G(180 + \theta_1) + m_2 G(180 + \theta_2) \quad (3)$$

and

$$q_4 = m_1 G(270 + \theta_1) + m_2 G(270 + \theta_2). \quad (4)$$

Equations (1)–(4) can be rewritten as

$$\begin{bmatrix} G(\theta_1) & G(\theta_2) \\ G(90 + \theta_1) & G(90 + \theta_2) \\ G(180 + \theta_1) & G(180 + \theta_2) \\ G(270 + \theta_1) & G(270 + \theta_2) \end{bmatrix} \begin{bmatrix} m_1 \\ m_2 \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix}. \quad (5)$$

From the radiation pattern, the gain $G(\theta)$ is known at every angle and the task is then to solve for m_1 and m_2 .

The solutions for m_1 and m_2 for all combinations of θ_1 and θ_2 are found using the following equations:

$$\begin{bmatrix} G(\theta_1) & G(\theta_2) \\ G(90 + \theta_1) & G(90 + \theta_2) \end{bmatrix} \begin{bmatrix} m_1 \\ m_2 \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}. \quad (6)$$

This process is then repeated using equations

$$\begin{bmatrix} G(\theta_1) & G(\theta_2) \\ G(180 + \theta_1) & G(180 + \theta_2) \end{bmatrix} \begin{bmatrix} m_1 \\ m_3 \end{bmatrix} = \begin{bmatrix} q_1 \\ q_3 \end{bmatrix}. \quad (7)$$

The correct solution occurs when m_1 and m_2 have the same value at the same θ_1 and θ_2 for both sets of solutions. With noise added, the values of m_1 and m_2 derived from (6) and (7) will not be identical, so the closest match will be the best approximation to the true values and the variation in these values will be an indication of the noise level in the system.

In order to solve for the relative strengths and angular positions of two incident signals, three equations and, therefore, three of the four switch positions are required. In general, with an n -element array it is possible to solve for $n - 1$ unknown signals.

This algorithm will provide a solution for multiple signals within the same quadrant, however, the array does not have

beamforming capabilities and so it is not possible to separate the signals.

IV. CONCLUSION

A novel electronically steerable antenna array using switched parasitic elements has direct application to direction finding in mobile communications systems for efficient base-station tracking. It has been shown that such an antenna can be used to determine the angular position of a distant source relative to the position of the receiver with minimal system requirements. With noise of -20 dB added to the system, the error in angle determination was found to be less than 5° .

This system can also be used to resolve multiple signals with the addition of some simple processing tools. The number of signals resolvable depends on the number of elements of the array. With n elements, it is possible to resolve $n - 1$ signals.

This antenna type provides a simple solution to direction finding without the complex mechanically steerable or phasing parts required by previously presented systems.

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