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ANTENNA SYSTEM MODEL FOR DIRECTION OF ARRIVAL ESTIMATION SYSTEM IMPLEMENTATION

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Abstract - Direction of Arrival (DoA) estimation is the process of finding the angular location of a radio device relative to a reference point (base station). In received signal strength (RSS) based DoA estimation, antennas are used with suitable algorithm to classify user angular locations. With an Omni-directional antenna, it is not possible to differentiate one angular location from another based on the measured RSS. Normally, multiple antennas are used in an array to obtain directional main beam for DoA estimation. This adds to the cost and complexity of the DoA estimation system. This paper presents an antenna array model with the minimum possible number of antennas in an array that is suitable for DoA estimation in wireless networks. A single 6-dipole collinear antenna was modelled and simulated in Computer Simulation Technology (CST) microwave to obtain an Omni-directional radiation pattern with high gain of 9.48dBi. The collinear antenna was further simulated as an array of two antennas to obtain a directional beam with a gain of 13.8dBi on broadside which was steered to other directions by changing the phases of individual antennas. Results have shown that each angular position is uniquely defined by only a single beam position which makes it suitable for RSS-based DoA estimation.

Key words: Antenna array, Direction-of-Arrival (DoA), Received Signal Strength (RSS), Collinear antenna.

I. Introduction

In wireless communications, antennas are means of coupling the transmitters to receivers using free space as a medium of propagation. The radiated energy of an antenna is characterized by its radiation pattern which is the graphical representation of the radiation properties of the antenna as a function of spherical coordinates (θ, φ). Antennas can be Omni-directional or directional. Omni-directional antenna is an antenna that radiates its energy equally in all directions. The simplest though not practical type is the isotropic antenna which is used as a reference antenna to quantify other antennas. The simplest and most popular practical Omni-directional antenna is a half-wave dipole which has a gain of approximately 2.14dB above isotropic in all angular directions on azimuth plane. When a dipole antenna is mounted so that it is vertically oriented with respect to ground, maximum energy is radiated towards the intended coverage area and nulls pointing up and down producing a toroidal pattern as shown in Figure 1 which is the radiation pattern of a single half-wave dipole antenna modelled and simulated on Computer Simulation Technology (CST) microwave at a frequency band of 2.4GHz to 2.5GHz.

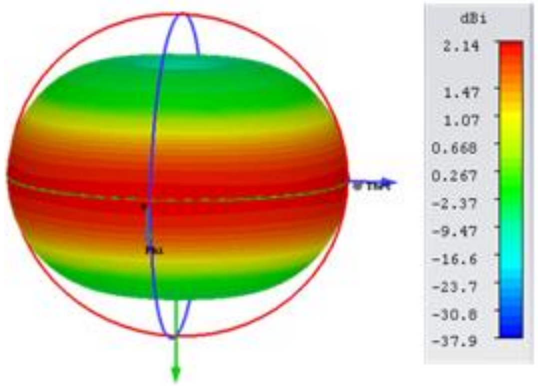

Figure 1: A single half-wave dipole antenna model showing Omni-directional radiation pattern on azimuth

With an Omni-directional antenna, it is impossible to classify user’s direction of arrival (DoA) based on measured RSS because in all azimuth locations and at same distances the antenna has equal gain.

A directional antenna or beam antenna is an antenna which radiates or receives greater power in specific directions allowing for increased performance and reduced interference from unwanted sources. For satellite and space applications, antenna directionality matters in both azimuth and elevation plane, but in most terrestrial wireless communications applications, directionality only matters in azimuth or horizontal plane. The dish is the most common directional antenna for consumer applications normally used for satellite communications. Yagi-uda (Kittiyanpunya & Krairiksh, 2017), quad (Prinsloo, Meyer, Maaskant, & Ivashina, 2015) and helical (Kumar, Kumar, Kumar, & Srinivasan, 2017)antennas are other types of directional antennas. By mechanically steering these 3 antennas, users can be classified for DoA estimation based on measured RSS from each steered direction. Antennas can be combined in an array to obtain a directional beam (Kapusuz, Sen, Bulut, Karadede, & Oguz, 2016)and be electronically controlled by phase, amplitude or both to steer the main beams to other directions for DoA estimation. An antenna array is two to thousands of antenna elements that are so spaced and phased such that the individual element’s contributions add constructively in one direction and destructively in another direction. These element clusters are used in applications like DoA estimation system where a single antenna element does not meet the required gain and radiation pattern. Common geometries for antenna arrays are linear, planar, circular or conformal. The arrangement can be in one or two dimension (Nikfalazar et al., 2017). Common elements used in antenna array systems are dipoles, monopoles, printed patch design or Yagi-uda. Every antenna exhibits a particular radiation pattern but when they are combined in an array, the overall radiation pattern changes due to the array factor (AF) which quantifies the effect of combining radiating elements without an account of the individual patterns. The overall array radiation pattern is a combination of the array factor and the element radiation pattern. The array factor depends on the number of elements, the element spacing, and amplitude and phase difference between the elements. The number of elements and the element spacing determine the aperture of the overall radiating structure. A typical antenna array system is characterized by multiple elements because array directivity increases with the number of elements. Unfortunately, the number of side lobes and the side lobe level increase as well. On the other hand, cost, size, and complexity also increase. The larger the element spacing the higher the directivity but then grating lobes which is an undesirable peak occurs. A grating lobe that is the same amplitude as the beam peak occur at element spacing that is equal to the wavelength beyond which the array becomes unusable due to multiple high grating lobes. This paper therefore presents CST microwave simulation of two antenna element array suitable for Direction of arrival estimation of users in a wireless network.

2 Broadside and Endfire Array

Antenna array can be designed as broadside and endfire array. A broadside array is simple and characterized by elements with uniform spacing, no phase difference and same power feeding. Endfire array, are characterized with progressive phase difference between element in an array which makes the feeding network more complex. Considering two antenna elements in an array 4 design, the normalized electric field at a point in far field is given by Equation (1) and 2 for broadside and endfire designs respectively.

$$E = \cos((\pi/2)\cos\theta) \qquad \textbf{(1)}$$

$$E = \sin((\pi/2)\cos\theta) \qquad \textbf{(2)}$$

This gives a maximum radiation pattern at 90° and 270° nulls at 0° and 180° for broadside but a maximum radiation at 0° and 180° nulls at 90° and 270° for endfire. Figures 2a and 2b show the bi-directional radiation pattern of broadside and endfire design with main beam perpendicular to array orientation and in the same direction as the array orientation, respectively.

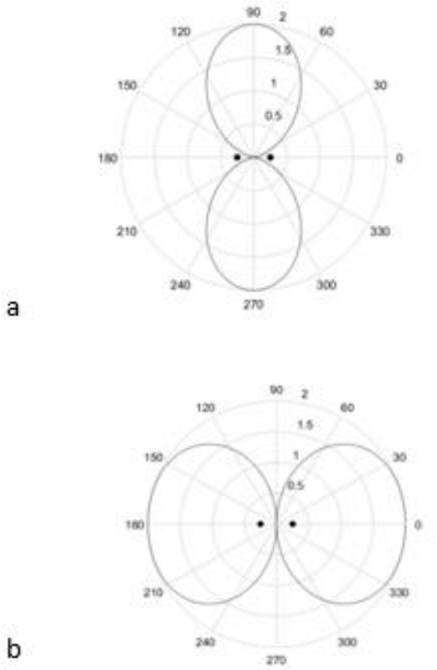

Figure 2: Radiation pattern for a 2-element array showing main beam on (a) broadside (b) end-fire.

Just as expected from analytical calculations, two symmetric peaks are obtained in each case. Broadside beam has a half power beam width of 60° as against the endfire design that has a beam width of 120°. For this study, broadside design is adopted, and phase weighting beam steering approach will be used to create azimuth positions at endfire and between broadside and endfire for DoA estimation.

3 Adaptive Antenna Systems

Adaptive antenna system can steer the antenna main beam in the direction of signal of interest (SOI). Some can steer nulls in the direction of interference. These use multiple antennas in either a phased array, a mechanically steerable antenna or reconfigurable antenna system (Kaemarungsi, 2005). Mechanically steerable antenna systems involve the use of electromechanical devices such as stepper motor (M Malajner, Cucej, & Gleich, 2012) to rotate the antenna main beam over coverage area. The additional hardware increases the overall cost and power consumption. Reconfigurable antennas are capable of dynamically modifying its frequency and bandwidth, polarization or radiation pattern in a controlled and reversible manner. It works like a phased antenna system but often comprises of only a single antenna element (Hakkarainen et al., 2014). In multiple antenna system, two or more antennas are used in an array to produce a beam that is electronically steered to multiple directions to receive signals and estimate the AOA and distance for localization (Arbula, 2008). Using multiple antennas is straight forward and adaptiveness can be achieved. One advantage of an adaptive antenna is that it improves signal-to-noise ratios (SNRs) by means of beam-forming techniques. Beamforming operates by manipulating the amplitude and phase vector of two or more input signals to create modified output signals. In this case, instead of physically moving the antennas, the beam is steered electronically to ensure reception in a desired direction and a null in undesired direction. Adaptive antenna can be switched beam or fully adaptive. Switched beam is a fixed beam approach where the beams are generated and fixed in different directions (Sivasundarapandian, 2015). Switched beam require large implementation area and they are not capable of separating signal of interest from interfering signals. Therefore, they are prone to be affected by noise and co-channel interference. In fully adaptive approaches, a main beam is produced and manipulated to the desired direction and nulls can be steered to undesired direction at any time. This can be achieved by using a phased array antenna system that manipulates the amplitude and phase of two or more signals arriving at the antenna system to form a vector of complex weight. Performance is characterized by the number of antenna elements, array geometry, antenna type and element spacing. Different antenna array structures have been proposed for localization estimations but the most common is the linear arrays geometry from where most other configurations emanate (Meng-Chang et al., 2011). Normally multiple antenna elements are used to achieve localization. The more the antenna elements, the more complex the system and the more the cost of implementation. Adaptive localization is achieved with adaptive antenna system accompanied by an adaptive algorithm (Karthiga, Preethi, & Devi, 2014) or only an adaptive localization algorithm (Marko Malajner, Gleich, & Planinšič, 2015). In general, the performance of an antenna array (for whatever application it is being used) increases with the number of elements in the array but unfortunately with increased cost, size, and complexity. Therefore, in this study, two antenna elements are considered.

4 Antenna Array Feed Network

Depending on the desired array characteristics, elements in an array are excited using amplitude/phase shift devices, or the feed network, or a combination of both. Three common feed networks are parallel, series and hybrid approach. In a parallel approach a.k.a corporate feed network, elements are feed from one source using parallel connections. This is achieved using RF power splitters or combiners. In a series fed network, elements are fed from one source using series connection so that as the signal travels from one antenna point to the other from source, antennas tap the power resulting in an uneven power distribution among the antennas. At one wavelength transmission line length, the elements are fed with same phase at that frequency. By changing the frequency, electrical length of transmission line changes thereby changing the phase between elements. In this way frequency scanning method is applied to steer the broadside beam to other directions. Hybrid approach is a combination of both parallel and series approaches in one feed network for instance a series-fed groups of elements, fed by a common signal from a parallel feed structure. Since the design in this research considers only two antenna elements, parallel or series feed networks are considered as two possible feed network configurations as shown in Figures 3a and 3b, respectively.

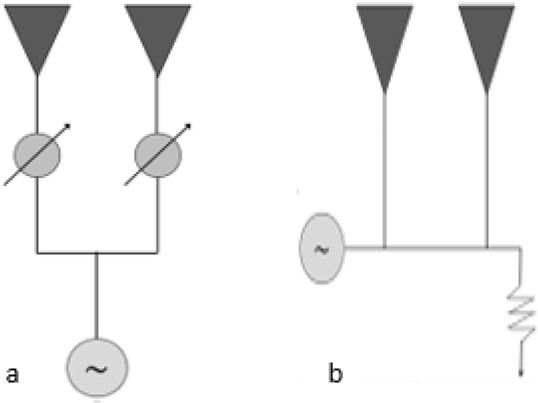

Figure 3: Possible antenna array feed networks for 2 element array system (a) parallel (b) series

Series approach has an advantage of reduced losses because no phase shift devices are required but power fed to each antenna are unequal. Since a broadside design was adopted in this study, same power feed to each element of the array is required. One advantage of a parallel feed network is that equal power is fed to all elements, therefore a parallel configuration is simulated. Complexity of an array system is highly dependent on the feed network. Three main factors that contribute to the complexity of any feed network are number of elements, the amplitude and/or phase distribution and the beam steering ability. Though an array with unequal power and phase distribution to the individual elements is used to modify the sidelobe level, directivity and direction of the main lobe, arrays with equal power and phase distribution are simpler and easier to implement. Also, a deep null is achieved when the amplitude ratio between the antenna elements is unity and this is only achieved when the signals arriving at both elements have equal amplitude. When power distribution is optimized to reduce side lobe levels (Ogurtsov & Koziel, 2017), efficiency is reduced and when phase distribution is optimized (Morini, Farina, Rozzi, & Venanzoni, 2006) for beam steering, side lobe may occur. To keep the antenna system model simple and less complex, minimum possible number of antenna elements, equal power and phase distribution, simple electronic only-phase steering control with equal amplitude to ensure total cancellation at directions of no interest are considered.

5 Antenna Model for DOA Estimation

The higher the gain of an antenna in any direction, the better the signal received in that direction. A high gain collinear antenna was modelled and simulated in CST using dipole elements. The relationship between gain and number of elements in a collinear array is given as; Gain(dBi) = 10log(n) + 2.14dBi where n is the number of elements and 2.14dBi is the gain of a single dipole element. Analytically, with six dipole elements collinear design a gain of 9.93dBi gain is expected. A six-element collinear antenna was modelled in CST using parameters of Table I to obtain a gain of 9.45dBi and an Omni directional pattern as shown in Figure 4.

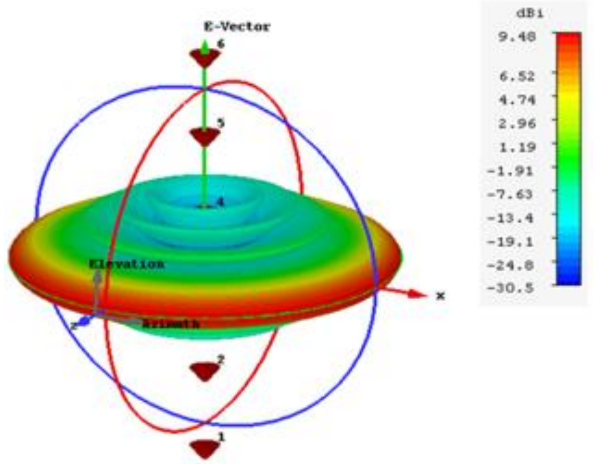

Figure 4: High gain collinear antenna model on CST

An optimization factor of 0.956 was used to optimize the antenna design to resonate at centre frequency of 2.45 GHz. The modelled high gain collinear antenna was then simulated as a two-element array on CST at pre-calculated phase combinations of (0°, 0°), (127°, 0°), (0°, 127°), (180° 0°) and (0° 180°) for (antenna 1 and antenna 2) respectively. These antenna phase combinations place the main beam at desired directions of 0°, −45°, 45°, −180° and 180°. Considering possible phase steps for implementation purposes, (0°, 0°), (120°, 0°), (0°, 120°), (180°, 0°) were simulated. The modelled collinear antenna was simulated in far-field as an array of two elements oriented on z-axis and separated by λ/2. The elements were simulated for these five selected phase states for the two antennas. The radiation pattern for each phase state was obtained as shown in Figure 5 and the result summarized in Table 1.

Table 1: Collinear antenna CST modelling parameters

Parameter	Value
Frequency, f (GHz)	2.45
Radio wave speed, c (m)	3×10^8
Wavelength (mm)	u × 1000 × (c/f)
Dipole radius, r (mm)	λ/1000
Dipole length, L (mm)	0.475 × λ
Optimization factor, u (mm)	0.965 × λ

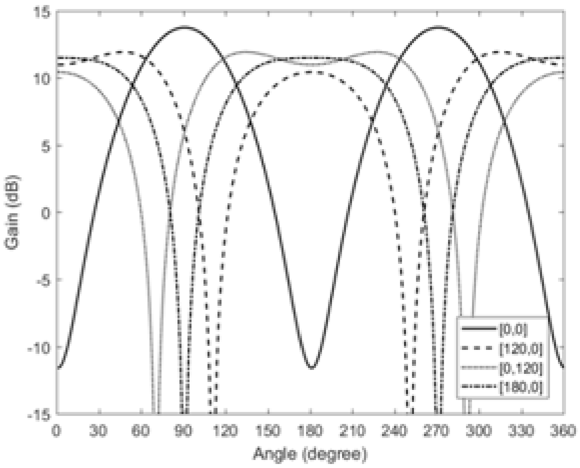

Figure 5: Array radiation pattern simulation on CST

5 Result Analysis

From the simulation result of Figure 5, it should be noted that only 4 phase combinations are represented. This is because phases (180 °, 0 °) and (0 °, 180 °) produce similar radiation pattern therefore only four out of five phase combinations can be used while the fifth state be captured in the DoA estimation algorithm saving time on switching. The simulation result of Figure 5 is summarized in Table 2.

Table 2: Antenna array radiation pattern simulation on CST

Items	(0°, 0°)	(120°, 0°)	(0°, 120°)	(180°, 0°)	(0°, 180°)

Min beam Angle (^{o})	-117	-158	-62	-159	-21
Max beam Angle (^{o})	-63	-118	-22	159	21
Beamwidth (^{o})	54	40	40	41	42
Beam peak gain (dBi)	13.8	11.9	11.9	11.5	11.5
Beam peak angle ((^{o})	-90	-134	-46	-180	0

From table 2, with antenna array, a directional beam can be achieved and with varying individual antenna phases, the main beam can be steered to other directions. With a good DoA estimation algorithm, the direction of users in a wireless network can be calculated based on the beam position where maximum RSS was measured compared with other beam positions. Also, because RF energy is focused only in one direction, higher gain of 13.8dBi was obtained at broadside as against 9.48dBi gain of a single collinear antenna. This means that better reception will be achieved in the direction of interest at any time. Another interesting outcome of this simulation is that even with only two antenna elements, at far field, each azimuth angle is uniquely defined by only one beam position when only 180° coverage is considered. This is an indication that the accuracy of the DoA estimation algorithm is assured. This result have also shown a wide beam width for each main beam position showing that this array model can only be applied where a precise angular location is not needed like in the strategy for small cell deployment in HetNet proposed in (Abonyi, 2019) where only an area location is required. The more the number of antennas in an array, the narrower the beam width, therefore this model can be upgraded for precise DoA estimation by increasing the number of antennas forming the array but at a higher cost and complexity. Therefore, for a simple and cost-effective application requiring only a sector DoA estimation, the presented antenna array model is ideal.

6 Conclusions

This paper presented a CST microwave model of a two-element antenna array system suitable for DoA estimation where a precise location is not required. A collinear antenna consisting of six dipole elements was modelled and simulated on CST to obtain an omni-directional radiation pattern with a gain of 9.48dBi. It was then simulated as an array of two elements to obtain a gain of 13.8dBi when both elements are in phase. By adjusting antenna phases to other pre-calculated values, the broadside beam was steered to other locations left and right of broadside but with reduced peak gain. Each azimuth angle has only one beam position that uniquely defines it based on maximum RSS. This means that the two-antenna array model can be used to accurately resolve DoA of users in a wireless network. With only two antennas for DoA estimation, system cost and complexity are reduced. Future work will include the investigation of the effect of the reduced gain when main beam is steered to other positions on localization accuracy.

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