Direction of Arrival Estimation Improvement for Closely Spaced Electrically Small Antenna Array

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ABSTRACT

In this paper, a new technique utilizing a scatterer of high dielectric constant in between electrically small antennas to achieve good Direction of arrival (DOA) estimation performance is demonstrated. The phase information of the received signal at the antennas is utilized for direction estimation. The impact of the property of the scatterer on the directional sensitivity and the output signal to noise ratio (SNR) level are studied. Finally the DOA estimation accuracy is analyzed with the proposed technique under the consumption of white Gaussian noise environment.

Key Words:
Biologically Inspired, Direction of Arrival (DOA), Electrically Small Antenna Array, High Permittivity

INTRODUCTION

Direction of arrival (DOA) of a microwave signal is important for many commercial [1] and military applications [2]. A typical microwave direction finding system requires a large number of antenna elements and sophisticated algorithms to achieve high degree of accuracy. However, the size, weight, and cost associated can be impractical especially for portable and commercial application. Thus accurate DOA estimation technique with small system size is highly desirable. Biologically inspired techniques are attractive for achieving compact and superior direction finding.

A very interesting biological system that is capable of direction finding for acoustic waves is the human auditory system which includes a pair of pinnae located at each side of the human head to collect acoustic signals, ear canals, eardrums, and cochlea to guide and detect incoming acoustic signals, and auditory nerves and neurons in the brain to process the detected signals. Human ears have the amazing ability to estimate arrival angle with accuracy up to 1° in the azimuth plane without ambiguity under binaural (utilizing two ears) condition [3]. The head functions as a low-pass filter. For most incident angles, one ear receives without the influence of the head while the other receives after the incident signal goes through (or around) the low-pass filter - human head. For higher frequency sound ($f > 3.0$ KHz; head is approximately half wavelength at 3 KHz), the head response function have an incident angle dependent attenuation as much as 20 dB [4]. This effect is often referred to as the head-related-transfer function (HRTF) which provides important cue for sound source localization for high frequencies. Figure 1 illustrates the HRTF effect, where x(t) is the incident sound signal and t is the time; $H_L(t)$ and $H_R(t)$ are the head-related responses at the left ear and right ear, respectively; $X_L(t) = (x * H_L)(t)$ and $X_R(t) =(x * H_R)(t)$ are the received sound signals at the left ear and right ear, respectively . The difference between $H_L(t)$ and $H_R(t)$ leads to both a phase and a magnitude difference (incident angle dependent) between the received signals at two ears. The combination of the phase (or time for transient signals) and amplitude information enables the human auditory system to have great localization capabilities for high frequency ranges. DOA technique using two antennas with a head like lossy scatterer in between them has been reported [5, 6].

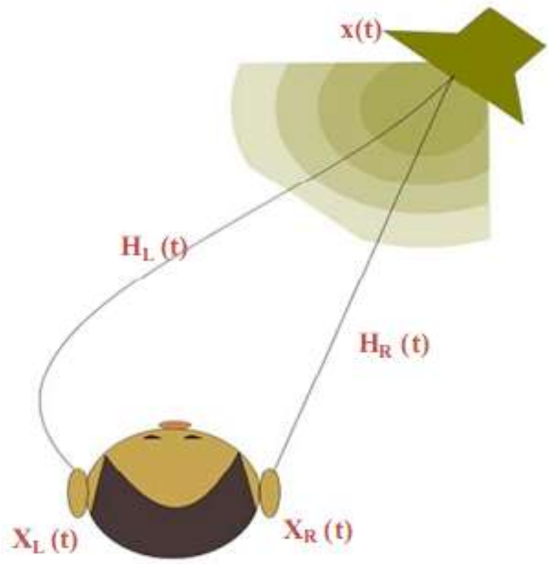

Figure 1. Utilizing the HRTF, human auditory system can achieve unambiguous direction finding for high frequency signals.

In this paper, a new technique with advantage of compact size utilizing a high-permittivity scatterer in between two electrically small antennas to enhance directional sensitivity is demonstrated. The impact of the scatterer properties (shape, dielectric constant) on the directional sensitivity is studied. Then the DOA performance of the system under white Gaussian noise environment is analyzed.

ANALYSIS OF HIGH-PERMITTIVITY-SCATTERER TECHNIQUE

Electrically small antenna array with small spacing between any two adjacent antennas is attractive because the size of the whole system can be reduced largely. With the incident angle dependent phase difference information of the received signal at the antennas, DOA can be estimated accordingly. However, the phase difference can be very small due to the space limitation. The challenge is how to achieve high accuracy of DOA estimation under this circumstance.

In this paper, two electrically small monopoles are placed close to each other (space much smaller than half wavelength) to reduce the total size of the structure. Figure 2 shows the two-electrically-small-monopole system model. The monopoles parameters are: length L = 70mm, diameter D = 1mm, spacing d = 50mm. The ground plane is of 70mm × 140mm. The system is modeled in the finite-element EM software ANSYS HFSS at frequency of 300MHz with excitation of incident plane wave from $\theta = 0^o$ to 90^o in the azimuth plane. Under this circumstance, the monopole length is only $0.07\lambda_0$ (electrically small) and the spacing is $0.05\lambda_0$, where λ_0 is the wavelength in free space. The phase difference of the received signal at the two monopoles in figure 2 follows to the first order as $\Phi(\theta) = 2\pi d\sin(\theta)/\lambda_0$. From the phase difference information, one is able to determine the incident angle of the plane wave because the phase difference is incident angle dependent. The steeper the phase difference is, the more angular sensitivity can be achieved. However, the maximum phase difference using the model in figure 2 is small, approximately 27^o. Assuming the space is now filled with a material with a dielectric constant of ε_r, then the phase difference becomes $\Phi'(\theta) = 2\pi d\sin(\theta)\sqrt{\varepsilon_r}/\lambda_0$, which is $\sqrt{\varepsilon_r}$ times larger than the free space case. It indicates the possibility of increasing the directional sensitivity by adding a scatterer with high permittivity in between two antennas, although the phase difference of the received signal would not be as simple as $\Phi'(\theta)$ because of the finite size of the scatterer.

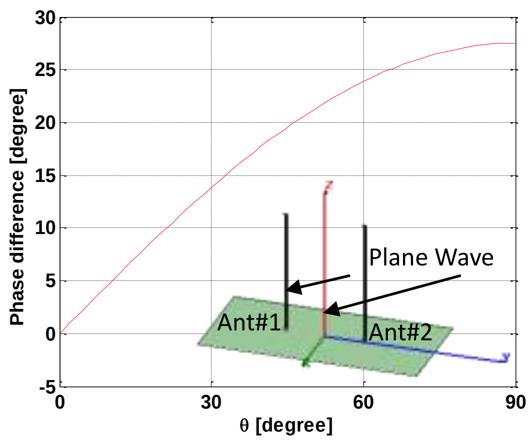

Figure 2. Phase difference of received signal at two monopoles vs. incident angle of plane wave from 0 - 90 degree (monopole length L = 70mm, diameter D = 1mm, spacing d = 50mm; Freq = 300MHz; modeled in HFSS).

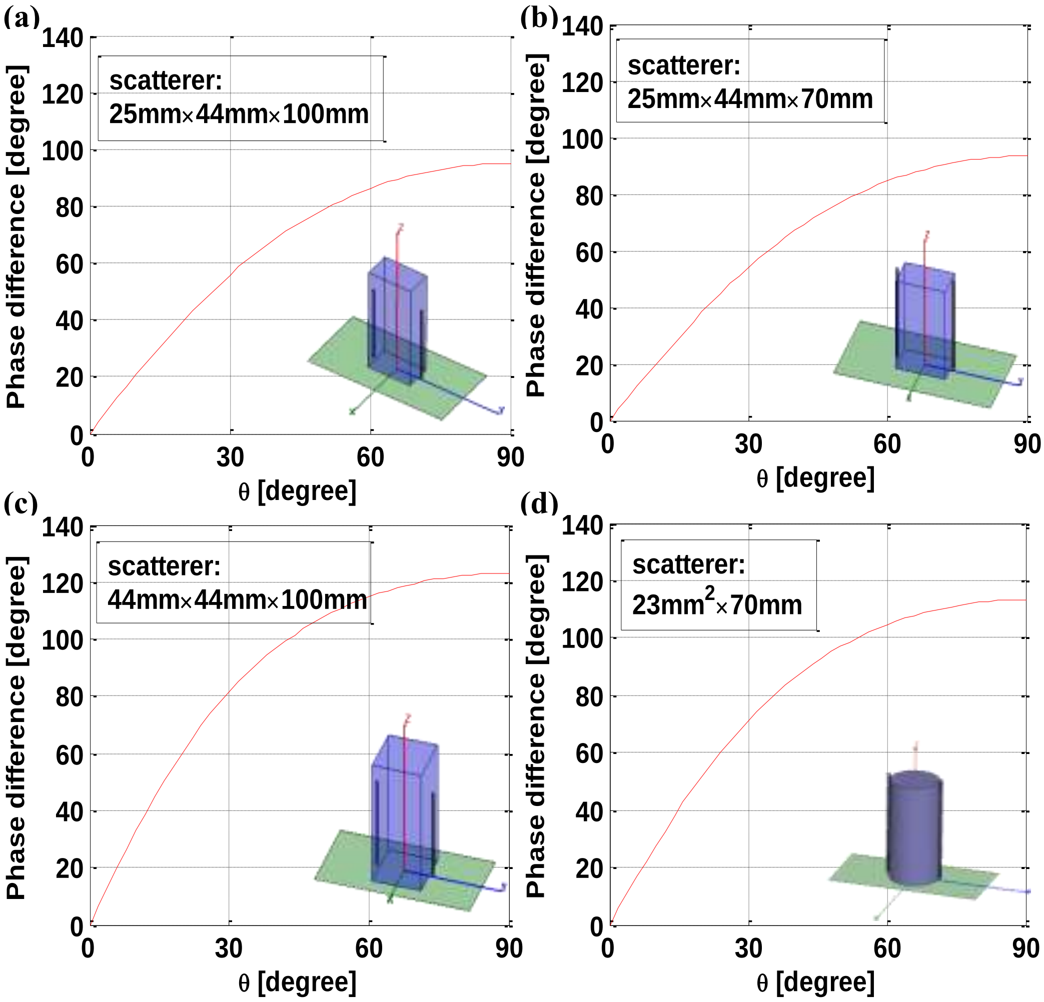

Figure 3. Phase difference of the received signal at two monopoles with various scatterers vs. incident angle (Rectangular prism: width × length × height and cylinder: radius × height; scatterer: $\varepsilon_r = 81$, $\sigma = 0.01$s/m; Freq = 300MHz).

In order to increase the direction finding sensitivity, a high-dielectric-constant scatterer is added in between the two monopoles. The scatterer is made of fresh water (naturally occurring water on the earth's surface in lakes, rivers, streams etc.. it excludes sea water.): $\varepsilon_r = 81$, $\sigma = 0.01$s/m. Figure 3 demonstrates the output phase differences of several two-monopole systems with various shapes of the scatterer. It can be clearly seen from figure 3 that by adding the scatterer, the curve of the phase difference vs. incident angle is steeper, which indicates the directional sensitivity is improved. When the height of the scatterer is larger than the length of the monopole, further increasing the height would not impact the received phase difference much. Scatterer of rectangular - prism and cylindrical shape does not seem to introduce much difference of the directional sensitivity.

As shown in Figure 4, the impact of the scatterer dielectric constant value is studied. The scatterer utilized is of size of 25mm × 44mm × 100mm. As the dielectric constant of the scatterer increases from 81 to 100, the slope of the phase difference also increases as expected, indicating an enhancement of the directional sensitivity. However, as it can be seen from figure 4(b), the received power level of the system (the incident plane wave is assumed to have an electric field at 1V/m) with higher dielectric constant is lower. It can be concluded that there is a tradeoff between the directional sensitivity and the received signal to noise ratio (SNR) using this structure.

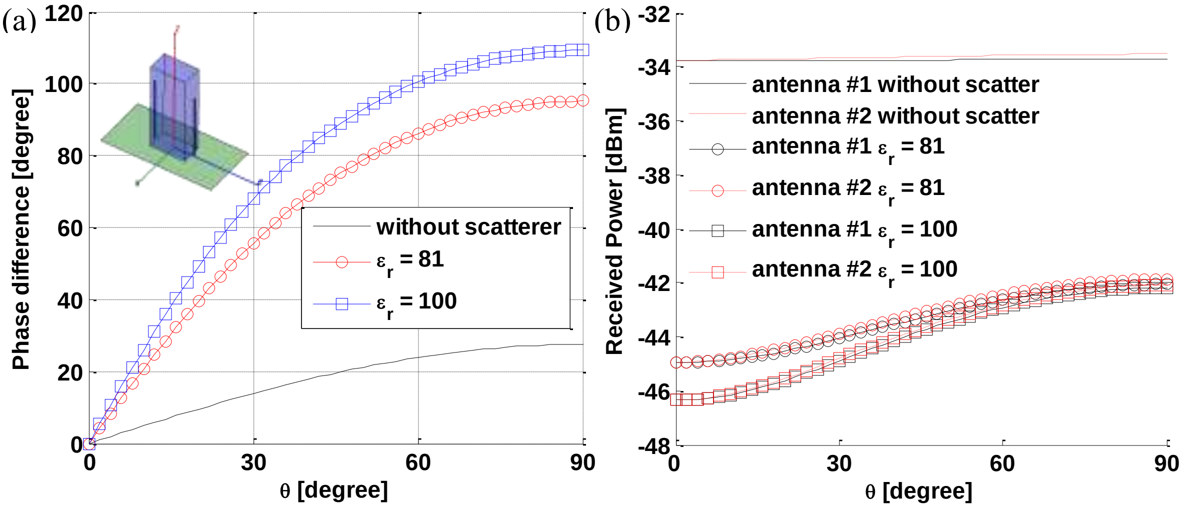

Figure 4. (a) Phase difference and (b) power level of received signal at two monopoles when the incident plane wave has and E field at 1V/m.

Figure 5 is another structure of scatterer used in the two-monopole direction finding system that may be important. The scatterer is made of fresh water ($\varepsilon_r = 81$, $\sigma = 0.01$s/m) and the size is 44mm × 60mm × 100mm, which means the two monopoles are embedded inside the scatterer. The simulation results in figure 6 shows that the system with the special scatterer has similar received phase difference but 10 dB higher received power level (the incident plane wave is assumed to have an electric field at 1V/m) compared with the system without any scatterer. This new system would have advantage when the SNR is critical to the DOA performance.

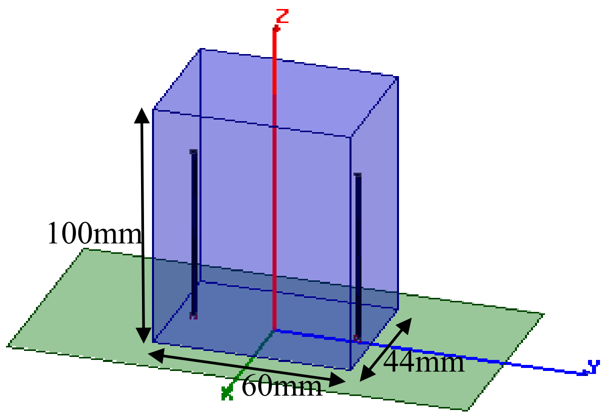

Figure 5. Model of two-monopole system with the two monopoles embedded inside a scatterer made of fresh water.

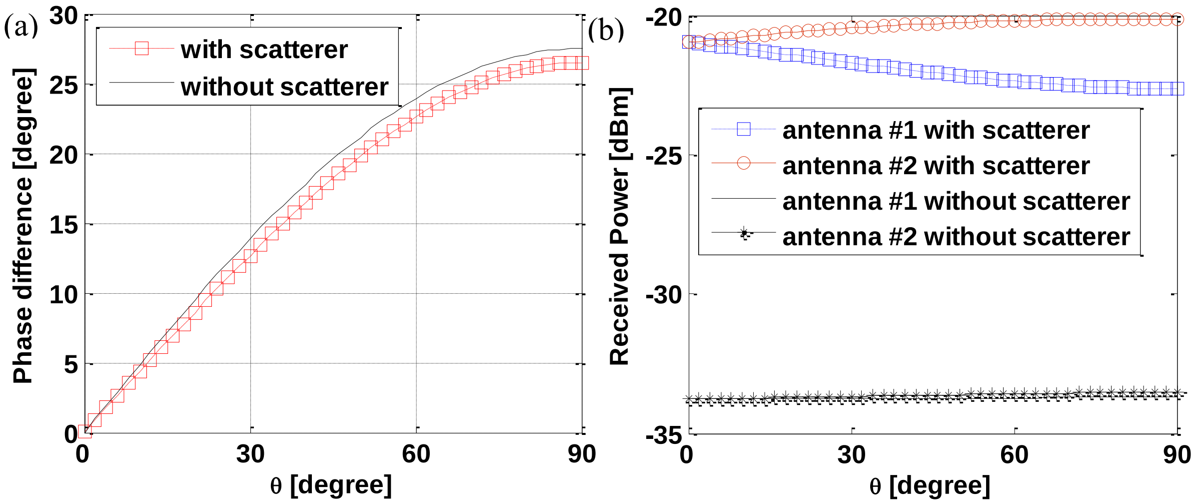

Figure 6. (a) Phase difference and (b) power level of received signal at two monopoles when the incident plane wave has an E field of 1V/m.

DOA PERFORMANCE SIMULATION

In order to have better understanding of the DOA estimation performance of the high-permittivity-scatterer technique in real case, the two-antenna system is modeled in HFSS with a third monopole located 1m away as a transmitter instead of incident plane wave as a source. The transmitter needs to be placed in the far zone of the two-monopole receivers so that the incoming signal at the two-monopole receivers is approximately plane wave. Under this circumstance, the output phase difference at the two antennas can be simulated and then be utilized in detecting the direction of the transmitted signal.

Figure 7 are the models of two-monopole systems with a third transmitting antenna. The specification of the model in figure 7(a) is: monopole length L = 70mm, diameter D = .25mm, spacing d = 50mm. The ground plane is of 150mm × 200mm. The added scatterer in figure 7(b) is of size 30 × 44 × 70mm^3 and made of TiO_2 anatase grade with $\varepsilon_r = 48$ and $\tan\delta = 0.002$. The TiO_2 anatase grade is chosen because it is solid and commercially available. The frequency simulated is 300MHz. The third transmitting monopole is of length of a quarter wavelength at 300MHz and the transmitter and receivers are set 1 m apart. We also have simulated models with transmitter and receivers 2 m and 3 m apart. The output phase difference shows almost no difference compared with that when transmitter and receivers are set 1 m apart, which ensures the transmitter is in the far zone of the two-monopole receivers for 1-m spacing. By rotating the transmitter from 0^o to 90^o, the phase difference and power level of the received signal vs. incident angle from 0^o to 90^o can be obtained. As a comparison, two-monopole system with plane-wave excitation is also simulated. The power level at the monopole transmitter is set to be 0dBm and the plane-wave excitation is of electric field of 89mV/m. Figure 8 plots the phase difference and received power level comparison of the system without scatterer using monopole as transmitter and plane wave excitation. And figure 9 are those with scatterer case. There is some discrepancy between the results using monopole as transmitter and using plane wave excitation. The phase difference discrepancy between the two cases is smaller than 8° and the received power level discrepancy are within 1dB for both without / with scatterer. The discrepancy may be as a result of limited simulation accuracy of the software. From figure 8 - 9, it can be seen that after adding a high-permittivity scatterer, the slope of the phase difference also increases as expected, indicating an enhancement of the directional sensitivity. However, the received power level is lower. There is a tradeoff between the directional sensitivity and the received SNR level.

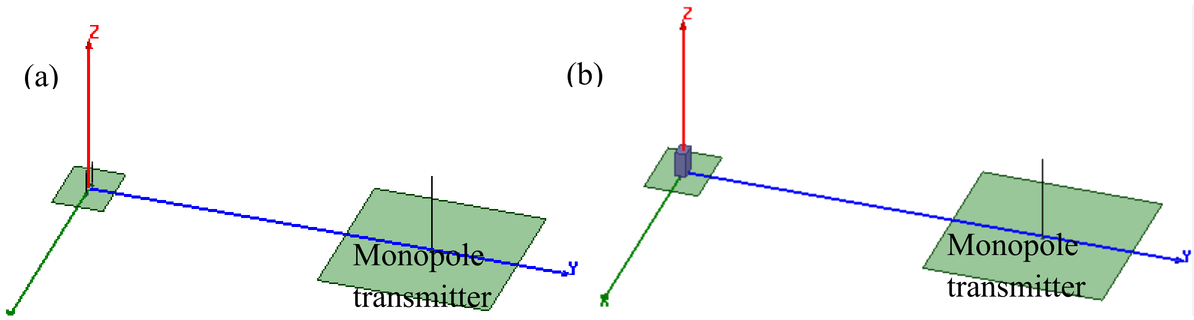

Figure 7. Setup of (a) two-monopole receiver without scatter and a single-monopole transmitter; (b) two-monopole receiver with a high-dielectric-constant material in between and a single monopole transmitter.

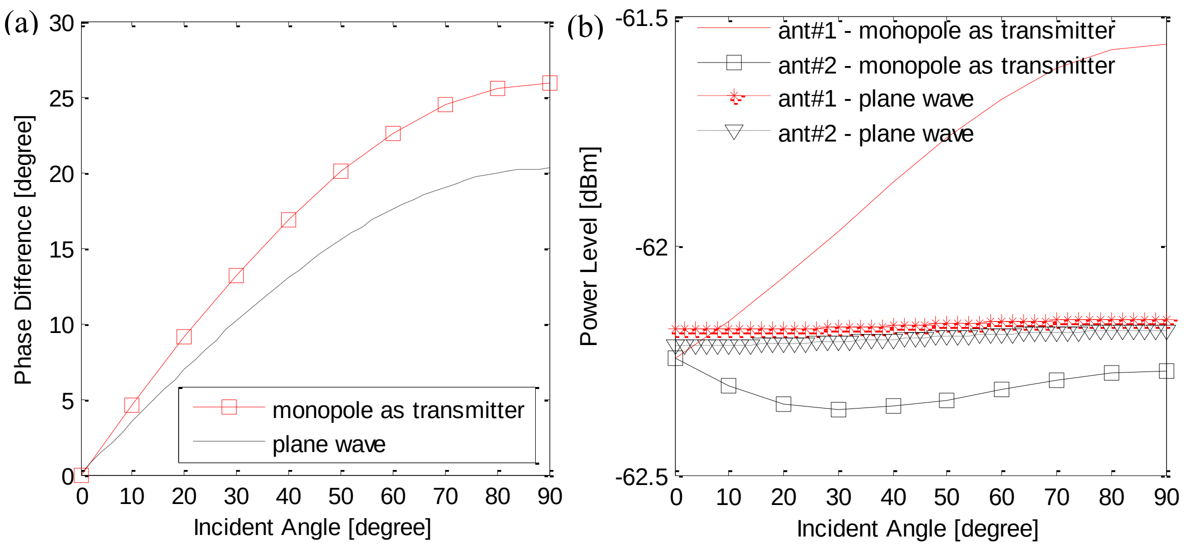

Figure 8. (a) The phase difference and (b) received power level comparison of the system without scatterer using monopole as transmitter and using plane wave excitation.

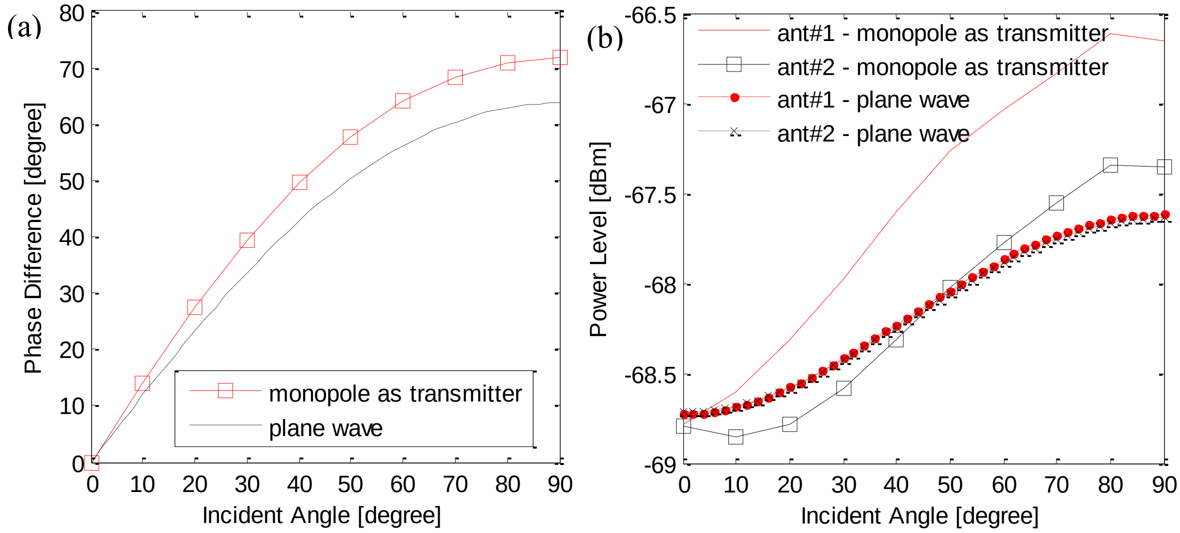

Figure 9. (a) The phase difference and (b) the received power level comparison of the system with scatterer using monopole as transmitter and using plane wave excitation.

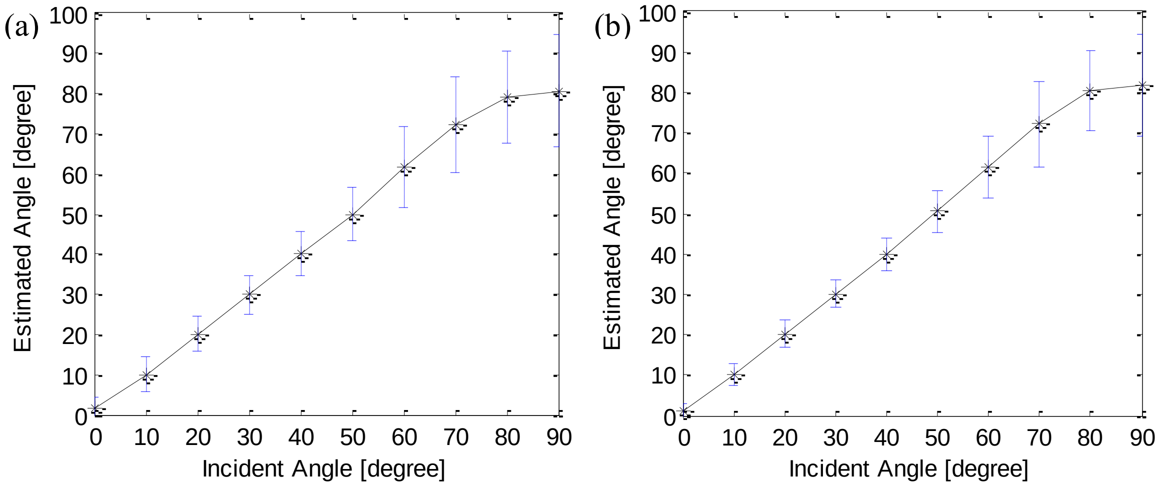

Figure 10. Average estimated angle vs. incident angle with RMS error bars for system (a) without scatterer and (b) with TiO_2 scatterer (noise level -62dBm, transmitter 0dBm).

In order to obtain the DOA performance of the proposed technique, an environment of white Gaussian noise is assumed and the average DOA estimation error under this circumstance is calculated. The DOA estimation method is Maximum Likelihood – the estimated DOA is the angle with minimum difference between the test phase difference (φ) and the calibrate phase difference ($\phi(\theta)$) obtained a priori:

$$\hat{\theta} = \min_{\theta} |\varphi - \phi(\theta)| \quad (1).$$

The noise level in the system is determined by the RF detecting device and here we assume the noise floor is of -62dBm when the transmitter power level is 0dBm. The simulation is run in matlab software with results analyzed after 1000 runs. Figure 10 shows the detailed DOA estimation performance of the two-monopole without / with TiO_2 scatterer using a third monopole 1 m away as the transmitter. It demonstrates the average estimated angle vs. incident angle with root mean square (RMS) error bars also plotted. It can be seen that there is an improvement of the DoA accuracy after adding a high-permittivity scatterer. In addition, the estimation accuracy is lower when the incident angle is higher (up to 90degree) due to lower directional sensitivity.

CONCLUSION

In this paper, a new technique utilizing high-permittivity scatterer in between electrically small antennas to achieve good DOA estimation performance is demonstrated. With higher dielectric constant, the directional sensitivity can be also larger. Both plane wave incident model and a model using a monopole antenna as transmitter are simulated. The impact of the shape of the scatterer to the directional sensitivity is studied and a system of special scatterer structure with improved output SNR is proposed. The DOA estimation error under the consumption of white Gaussian noise environment is calculated. The simulation results do show an improvement of the DOA estimation accuracy after adding a high-permittivity scatterer.

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