TẠP CHÍ KHOA HỌC VÀ CÔNG NGHỆ NĂNG LƯỢNG - TRƯỜNG ĐẠI HỌC ĐIỆN LỰC
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A ROBUST DIRECTION OF ARRIVAL ESTIMATION SYSTEM FOR MILLIMETER-WAVE APPLICATIONS

HỆ THỐNG ƯỚC LƯỢNG HƯỚNG SÓNG TỚI ỨNG DỤNG CHO THÔNG TIN VÔ TUYẾN DẢI TẦN MILIMET

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Abstract:

Millimeter-wave wireless communications systems are proving many advantages in comparison to systems operating at the lower frequency band thanks to their wide bandwidth, ability to provide high-speed and multimedia services. However, the transmission loss in the system is large, so it is necessary to have beam forming to compensate for this loss as well as to implement interference reduction techniques in order to increase system quality. In order to perform beam forming, determining the direction of arrival (DOA) of the incident wave of the radio signal source is a necessary condition. This paper proposes a millimeter-wave multi-antenna system for the estimation of DOA of radio signal in the azimuth plane operating at 28 GHz. The proposed system for determining the DOA of correlated and uncorrelated signals in millimeter-wave applications utilizes the digital intermediate frequency (IF) software-defined radio receiver architecture combining with a 90 degree phase shifter as an analog inphase-quadrature demodulator and multipath signal classification (MUSIC) algorithm associated with the improved spatial smoothing technique. The system is modeled and simulated to demonstrate the ability of determining the DOA of a radio signal operating at a center frequency of 28 GHz. The proposed system is modeled and simulated for the purpose of estimating the DOA of signal of interest at 28 GHz. The proposed solution is capable of estimating the DOA of the correlated and uncorrelated signals with high accuracy, an error of less than 1 degree, and a low number of samples (snap shots) by using software defined receiver architecture based on phase shifter and demodulation scheme by software, as well as super-resolution algorithms.

Key words:

Direction of Arrival, millimeter-wave multi-antenna system, super-resolution algorithms.

Tóm tắt:

Thông tin vô tuyến ở dải sóng milimet (mm) đang chứng tỏ nhiều ưu điểm so với các hệ thống ở dải sóng thấp hơn do băng thông rộng, khả năng cung cấp dịch vụ tốc độ cao, dịch vụ đa phương tiện. Tuy nhiên suy hao truyền sóng trong hệ thống lớn, do đó cần phải có định hướng búp sóng để bù đắp phần suy hao này cũng như thực hiện kỹ thuật giảm can nhiễu, tăng chất lượng hệ thống. Để thực hiện việc định hướng búp sóng, việc xác định hướng sóng tới của nguồn tín hiệu vô tuyến là điều kiện cần. Bài báo đề xuất một hệ thống nhiều anten xác định hướng sóng tới của tín hiệu vô tuyến ở mặt phẳng phương vị trong hệ thống vô tuyến ở dải sóng mm hoạt động ở tần số 28 GHz. Hệ thống xác định hướng sóng tới của tín hiệu tương quan và không tương quan trong hệ thống vô tuyến ở dải sóng mm dựa trên kiến trúc máy thu trung tần định nghĩa chức năng bằng phần mềm với bộ di pha tín hiệu 90 độ để thực hiện chức năng tương tự như bộ giải điều chế cầu phương và thuật toán phân loại tín hiệu đa đường kết hợp với kỹ thuật làm mịn không gian. Hệ thống được mô hình hóa và mô phỏng để minh chứng khả năng xác định hướng sóng tới của tín hiệu vô tuyến hoạt động ở tần số trung tâm 28 GHz. Giải pháp đề xuất có khả năng xác định hướng sóng tới của tín hiệu cả tương quan và không tương quan với độ chính xác cao, sai số nhỏ hơn 1 độ và với số lượng mẫu trong miền thời gian ít thông qua việc sử dụng kiến trúc giải điều chế, di pha bằng phần mềm và thuật toán có độ phân giải cao.

Từ khóa:
Hướng sóng tới, hệ thống vô tuyến đa anten dải sóng milimet, thuật toán độ phân giải cao.

1. INTRODUCTION

Millimeter-wave wireless communications systems have a lot of advantages such as the wide bandwidth, the ability to provide high-speed and multimedia services. These systems can be deployed in 5G and 6G mobile communications [1] as well as in radars [2]. In these systems, beamforming techniques are widely used to increase quality and performance because they can compensate for the huge propagation loss and reduce interference. In order to perform beam forming, determining the direction of arrival (DOA) of the incident wave of the radio signals is the first step [3] beyond the communication protocols. The estimation of the DOA of signals of interest still has a lot of challenges [4].

There are two kinds of conventional systems: single radio channel systems and multi-channel systems. For single radio channel systems, only one single receiver connected to a radio frequency (RF) switch is used with multiple antenna elements in the array. For multi-channel systems, one receiver is utilized for each antenna element in the array. The signals coming from all antennas are detected simultaneously by these receivers and then the baseband signal is obtained by using a classical analog or digital receiver. This acquisition is performed for each antenna element in the array and then the DOA information of signals of interest can be extracted by an existing algorithm. Software defined radio (SDR) receiver architecture is newly proposed. In this architecture, almost process of radio signals is implemented in the "digital domain" by a digital signal processor and this receiver can process digital communication signals as an analogue receiver. This SDR solution can be considered as a promising approach in the near future thanks to technology evolution. This approach has also some advantages such as it is easy to testing different kinds of receiver architectures without hardware changing by using software radio. It can also avoid nonlinear effects of RF analogue components or devices. Using this approach, it is possible to get reliability, accuracy, and low implementation costs thanks to its digital circuitry. In particular, with digital solution based on SDR, a lot of signal processing techniques or tasks that are not easily implemented in analogue receiver can be simply realized [5]-[7]. In this digital SDR receiver architecture, an analog-to-digital converter (ADC) is ideally connected after the receive antenna or after the low noise amplifier. The RF signal is directly digitized by this ADC and then a digital signal processor (DSP) in this receiver performs the other tasks such as frequency conversion, filtering, detection and so on. However, this receiver architecture requires high speed sampling ADC that is often not easy to realize and that can increase the implementation cost especially for millimeter-wave system.

With the evolution of RF CMOS technology, the requirement for a high sampling speed ADC can be overcome. It is not very difficult to design and implement a high speed ADC with a reasonable cost. Especially, some hardware developments proposed in [8] and [9] make the digital SDR receiver in multi-antenna system appear as a potential solution in the near future.

Some recent practical solutions for multiple antenna systems or adaptive antenna systems have been investigated [10]-[13]. However, these solutions are rather complicated, especially in DOA estimation procedure and they require high speed ADC and a large number of samples in receivers. In order to overcome these drawbacks, we develop in this paper a multi-antenna system to determine the azimuth DOA of the radio signals in millimeter-wave wireless system operating at 28 GHz. The proposed system utilizes the digital IF software-defined radio receiver architecture and multiple signal classification (MUSIC) algorithm associated with the improved spatial smoothing technique for DOA estimation procedure. In section II, we present the proposed multi-antenna system and signal processing for DOA estimation. In section III, the simulation results are shown. A brief conclusion is addressed in section IV.

2. SYSTEM ARCHITECTURE AND DOA ESTIMATION PROCEDURE

2.1. Digital intermediate frequency multi-antenna system architecture

Figure 1 proposes a robust millimeter-wave multi-antenna system for azimuth DOA estimation that is based on digital IF receivers combined with a phase shifter. The system comprises of a uniform linear array of M elements antennas connected to M digital intermediate frequency receivers combining with 90 degree phase shifters in analogue domain and a baseband digital signal processor. At one receiver, the RF signal after the receive antenna is delivered to the low noise block (LNB) in order to convert to the intermediate frequency and then it is divided into branches, one 90 degree phase shifted, and then digitalized directly by two analogue to digital converters (ADC).

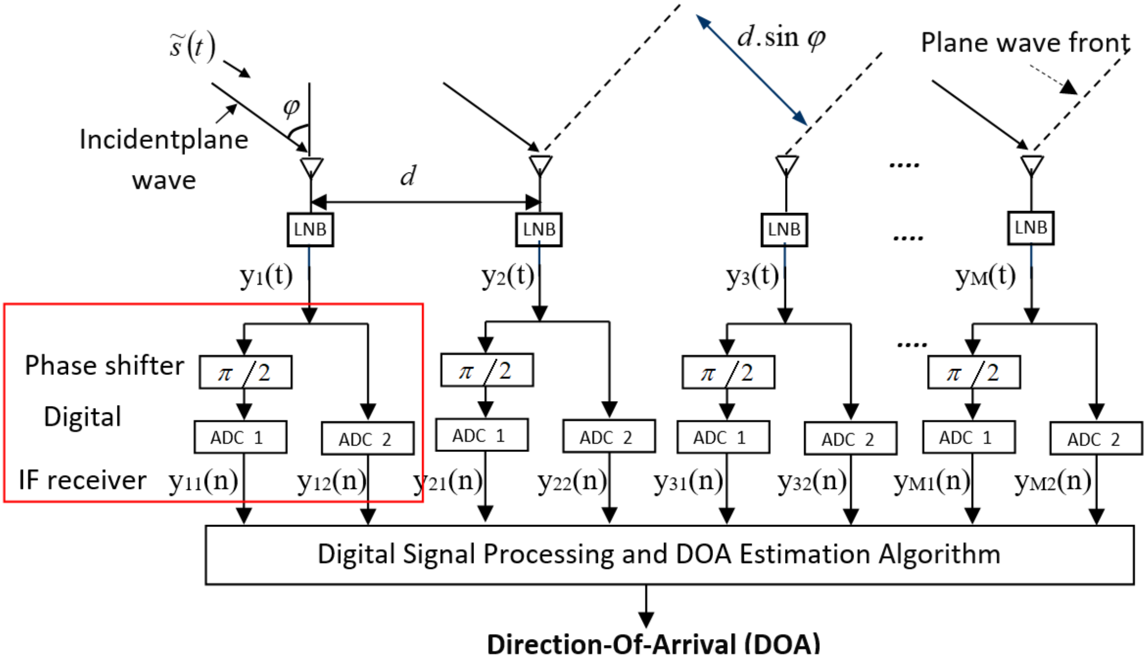

Figure 1. Direction finding system based on all digital receiver architecture for DOA estimation in azimuth plane

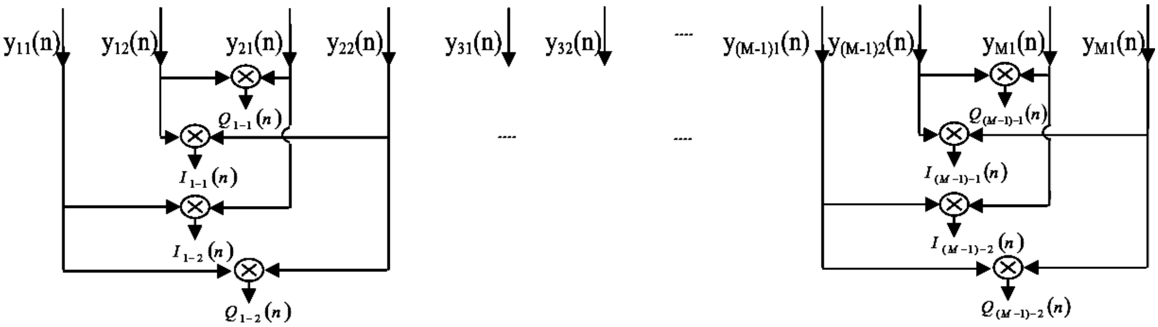

Figure 2. Digital signal processing for DOA estimation

In baseband, at the ADC's outputs, the discrete samples are collected and the signal complex envelops as well as the correlation products that include the phase and the amplitude of RF signal are calculated and then the output data vector of the array is planned. From this array data vector, the correlation matrix is determined and then information of the DOA of signals is estimated. There are two main approaches for the DOA estimation procedure. The first one is based on conventional beam-forming and the second one is based on high resolution algorithms. For the first approach, the angular resolution is rather low because it is limited to Rayleigh criterion depending on the number of antenna elements. For the second approach, the angular resolution can be much improved because it utilizes the super-resolution algorithms. However, it can also increase the computational time.

All procedures are performed in baseband and digital domain by a digital signal processor or a Field Programmable Gate Array (FPGA). Using the “physical” inphase-quadrature in each digital IF receiver, the RF signal can be sampled with a lower sampling frequency and with a small number of snapshots.

2.2. Digital signal processing procedure for DOA estimation

For explanation, it is assumed that there is one signal coming from azimuth direction-of-arrival ϕ impinging on the antenna array. For narrow-band hypothesis, this DOA characterizes a phase difference of signal between elements in the array and that is calculated from two measured signal complex envelops. The RF signal at the first antenna and the second antenna in time domain can be expressed as follows:

$$y_1(t) = Re\left\{A_1 e^{j2\pi ft}\right\} = A_1.cos(2\pi ft) \quad (1)$$

$$y_2(t) = Re\left\{A_2 e^{j(2\pi ft+\Delta\psi)}\right\} = A_2.cos(2\pi ft + \Delta\psi) \quad (2)$$

where A1 and A2 are their amplitudes.

$\Delta\psi$ is the phase difference of signal measured at two elements and it depends on the DOA:

$$\Delta\psi = \frac{2\pi d}{\lambda}\sin\varphi \quad (3)$$

d represents the element spacing and λ is the wave length.

The intermediate frequency signal is divided into 2 branches. The signal with a 90° shifted phase in the left branch and the signal in the right branch in analog domain can be expressed as the following:

$$\begin{aligned} y_{11}(t) &= Re\left\{\frac{A_1}{\sqrt{2}}.e^{j\left(2\pi ft+\frac{\pi}{2}\right)}\right\} \\ y_{12}(t) &= Re\left\{\frac{A_1}{\sqrt{2}}.e^{j2\pi ft}\right\} \\ y_{21}(t) &= Re\left\{\frac{A_2}{\sqrt{2}}.e^{j\left(2\pi ft+\frac{\pi}{2}+\Delta\psi\right)}\right\} \quad (4) \\ y_{22}(t) &= Re\left\{\frac{A_2}{\sqrt{2}}.e^{j(2\pi ft+\Delta\psi)}\right\} \end{aligned}$$

In analog receiver, $\Delta\psi$ is extracted from complex envelops after inphase-quadrature demodulators. In the proposed architecture, it is obtained by signal processing in the digital domain based on correlation product as shown in figure 2. In this procedure, the real and imaginary parts of the correlation product between $y_1(t)$ and $y_2(t)$ are obtained in the digital domain as the following:

$$I_{1-1}(n) = Re\left\{y_{12}(n).y^*{}_{22}(n)\right\} = \frac{A_1.A_2}{2}.cos(\Delta\psi) \quad (5)$$

$$I_{1-2}(n) = Re\left\{y_{11}(n).y^*{}_{21}(n)\right\} = \frac{A_1.A_2}{2}.cos(\Delta\psi) \quad (6)$$

$$Q_{1-1}(n) = Re\{y_{11}(n).{y^*}_{22}(n)\} = \frac{A_1.A_2}{2}.sin(\Delta\psi) \qquad (7)$$

$$Q_{1-2}(n) = Re\{y_{22}(n).{y^*}_{11}(n)\} = \frac{A_1.A_2}{2}.sin(\Delta\psi) \qquad (8)$$

The complex envelop of signal in baseband is then obtained as follows:

$$h_1(n) = I_{1-1}(n) + jQ_{1-1}(n) \quad \text{or} \quad h_1(n) = I_{1-2}(n) + jQ_{1-2}(n) \qquad (9)$$

The complex envelops of signal in baseband of the other receivers are determined by the same process between the first antenna element and the other ones in the array and then the array output vector is organized as:

$$y(n) = [h_1(n), h_2(n), h_3(n), \dots, h_{\text{M-1}}(n)]^T \qquad (10)$$

From this array output vector, the data covariance matrix in equation (10) is calculated by:

$$R_{\text{xx}} = E\{y(n).y(n)^H\} \qquad (11)$$

From the covariance matrix R_{xx}, a decomposition process is performed to get the signal subspace and noise subspace and it is assumed that two these subspaces are orthogonal, and the signals are incoherent. The next step, the projection of signal subspace and signal classification are determined in order to get the signal parameters. This method, a subspace-based and super-resolution named multiple signal classification (MUSIC), is deployed for the estimate of DOA of RF signals [14]. These subspaces are created from the eigenvectors of the covariance matrix R_{xx}. The pseudo spectrum of the MUSIC is expressed by:

$$P_{music}(\varphi) = \frac{1}{a^H(\varphi).E_N.E_N^H.a(\varphi)} \qquad (12)$$

Here, E_N is the eigenvectors that is associated with the noise subspace of the covariance matrix R_{xx}. H represents a complex conjugate transpose.

and $\mathrm{a}(\varphi) = [1,\ \mathrm{e}^{-\mathrm{j}\frac{2\pi \mathrm{d}}{\lambda}\sin\varphi} \ldots, \mathrm{e}^{-\mathrm{j}\frac{2\pi \mathrm{d}}{\lambda}(\mathrm{M}-1)\sin\varphi}]$ presents the M×1 steering vector.

One of the drawbacks of the MUSIC algorithm is that, it does not work correctly with coherent signals. So, for coherent signals, the coherence must be broken before using MUSIC algorithm. In this research, the improved spatial smoothing pre-processing (SSP) method is employed to “de-correlate” signals [15].

The following steps summarize the procedure for azimuth DOA estimation using the proposed multi-antenna system:

Step 1: Calculate the complex envelope of the signal in the discrete domain or calculate the correlation products (equation 9) at the outputs of the digital-to-analog converters (ADCs).

Step 2: Sort the received data vector y(n).

Step 3: Calculate the covariance matrix of y(n).

Step 4: Decompose to eigenvectors and eigenvalues from the covariance matrix of y(n).

Step 5: Determine signal space (K) and noise space (M-K) by arranging eigenvalues in descending order.

Step 6: Calculate the pseudo-spectrum of the MUSIC function, $P_{music}(\varphi)$.

Step 7: Estimate the incident wave direction of the signal by finding the maximum value of the MUSIC pseudo-spectral function, $P_{music}(\varphi)$.

3. SIMULATION RESULTS

To validate the performance of the proposed system for DOA estimation, we model and simulate it using Matlab. In the first simulation scenario, it is assumed that there are five incoherent signals arriving at a ULA of 8 elements at the DOA of -45°, -30°, 0°, 3° and 10°. The channel model noise is AWGN. The operation frequency of the system is 28 GHz and the RF signal is down converted to the intermediate frequency at 1210 MHz corresponding to the period T of 82.644 ns. The simulation time step of 41.322 ns corresponds to a 605 MHz sampling frequency, i.e. 1 point per signal period T. The number of snapshots is 1000 and the SNR is 15 dB for DOA estimation by MUSIC algorithm presented in the II section. Here, the frequency chosen is suitable for millimeter-wave communication applications. For the system where the conventional digital intermediate frequency receiver do not use 90 phase shifters, it requires a high speed sampling ADC and the sampling frequency is chosen so that there are at least 2 points per modulated symbol period. However, using the proposed system, the sampling frequency is lower thanks to the "physical" inphase and quadrature demodulator implemented by a 90 degree phase shifter. Figure 3 presents the simulation result of 5 incoherent signals. We can see from this figure that the 5 signals are accurately estimated with the DOA of -45°, -30°, 0°, 3.5° and 10°.

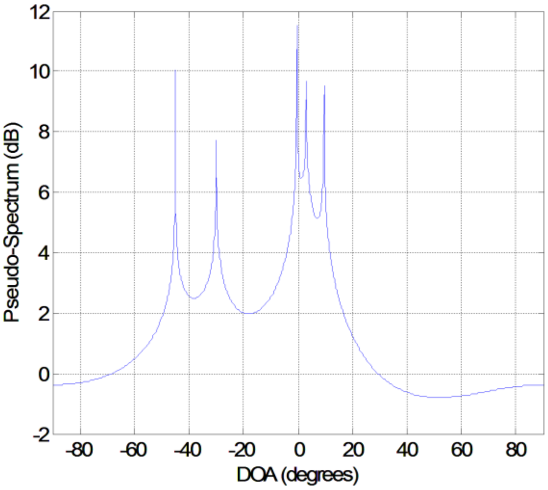

Figure 3. Simulation result of 5 incoherent signals at the DOA of –45°, –30°, 0°, 3° and 10°

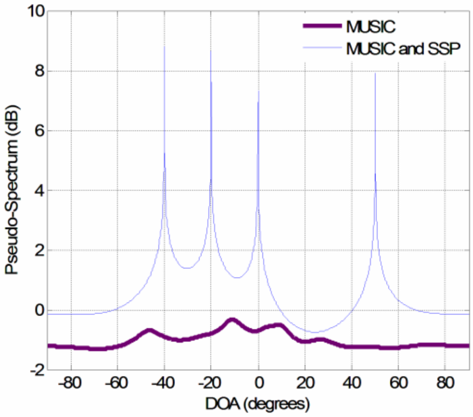

Figure 4. Simulation result of 4 coherent signals at the DOA of –40°, –20°, 0° and 50°

In the second simulation scenario, we

assume that there are 4 coherent signals arriving at the DOA of -40°, -20°, 0° and 50°. All four of these signals are completely coherent and the SNR is set at 15 dB. The number of samples per period and the number of snapshots is 1 and 1000, respectively. Figure 4 presents the simulation results for DOA estimation of these 4 coherent signals using the MUSIC algorithm and the SSP associated with MUSIC. It has been clearly seen that the MUSIC algorithm does not work for coherent signals. Here, the two coherent signals are not detected. However, the angles of arrival of signals are well estimated with the DOA of $–40^o$, -20^o, 0° and 50° when the MUSIC algorithm is associated with to SSP.

4. CONCLUSIONS

We propose a robust system for direction of arrival estimation in azimuth plane of millimeter-wave frequency signals. The proposed system consists of a uniform linear array followed by a “physical” inphase and quadrature demodulator in digital IF receiver architecture and a digital signal processor. The novel robust system could be developed for many applications in future mobile communications, in radar as well as in wireless positioning systems. The system is simulated for the test of DOA of RF signals. The DOA is estimated using the super-resolution MUSIC algorithm for incoherent signals and MUSIC algorithm associated with the improved spatial smoothing for coherent signals. The simulation results show that the DOA of RF signals can be accurately detected with this digital solution with the error smaller than 1 degree. The proposed system offers advantages over traditional one such as low sampling speed, reconfiguration possibility, and high estimation accuracy.

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