Experimental Demonstration of a Direction of Arrival Estimation Algorithm for mm-wave Broadband Communication Systems

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Abstract — **The experimental demonstration of a direction of arrival (DOA) estimation algorithm suitable for switched-beam array antenna operating in the millimeter-wave band is reported. The algorithm is based on power measurements and avoids employing the digital signal processing techniques which are commonly used in conventional DOA algorithms. Simulation and experimental results for the proposed algorithm using a four-element antenna array operating at 60 GHz have been obtained, showing an excellent agreement.**

I. Introduction

Fourth-generation (4G) mobile systems are envisaged for very high bit rate (broad band) applications. The *millimeter-wave* (mm-wave) band has been chosen to implement 4G-based applications due to the available spectrum and compactness of antenna and radio components [1]. Furthermore, smart antenna systems have been proposed to increase both system capacity and coverage area by reducing interference and multipath fading [2, 3]. One of the most important approach for smart antenna systems is the estimation of the direction of arrival (DOA), which is an essential task for user-tracking and location-based services. Conventional digital signal processing (DSP) based DOA estimation algorithms, such as MUSIC or ESPRIT, have been proven to achieve good results, however they require increased processing power and are thus difficult to implement in real time systems, especially in wideband mm-wave systems due to the envisaged high bit rates [4]. In this paper, we propose a novel DOA estimation algorithm for switched-beam array antenna based on power measurements, similar to the mono-pulse technique employed in radar systems [5], which avoids employing signal processing techniques [6]. Switched-beam array antenna is the simplest implementation of smart antenna systems and they are usually the first option to be considered in actual commercial wireless systems.

The proposed algorithm estimates the DOA of the impinging signal of interest using the following special properties of the mm-wave systems [7]: i) the strongest signal is always received from the line-of-sight (LOS) direction, ii) multipath components are largely attenuated due to the use of directional antennas at the base station (BS), and iii) interference sources may be highly attenuated if non-line-of-sight (NLOS) path is ensured between the interference sources and the mobile terminal (MT), as proposed in [1]. In this paper the influence of multipath on the DOA estimation error is evaluated and the algorithm is experimentally tested employing an antenna array of four elements operating at 60 GHz. Experimental results are compared with simulation results to evaluate the algorithm feasibility, showing good agreement.

II. Proposed Algorithm

Switched-beam antennas are employed at the BS to generate a set of beams instead of the conventional broad-beam covering the whole sector. For instance, N identical and orthogonal beams are provided by beamforming networks like the Butler matrix [8].

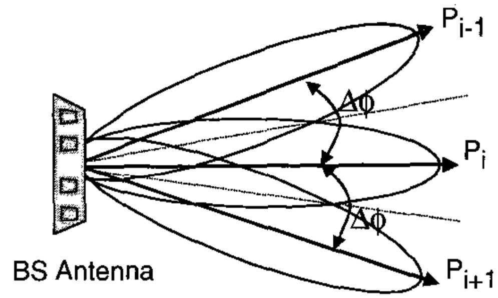

Fig. 1. DOA estimation algorithm. The dashed lines show the tracking d-estimator decision thresholds of ±1, $\Delta\phi$ is the angular range between the directions of maximum gain of adjacent beams and P_i, P_{i+1}, P_{i-1} are the powers measured with the i^{th}, $i+1^{th}$ and $i-1^{th}$ beam, respectively, where i goes from 1 to the number of beams.

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In a time division multiple access (TDMA) system with no angular diversity, a single beam is activated at any given time giving service to a single MT. The selection of the activated beam for the MT is based on a number of parameters, among which the received signal-strength indicator (RSSI) and the DOA information play the most important role.

DOA estimations are implemented at the BS during uplink transmission. The proposed DOA algorithm employs three beams rather than the two beams usually employed in radar systems. Therefore, the received signal power at the BS is measured by pointing the antenna beam to the current MT position, (P_i), but also to the previous (P_{i-1}) and the following (P_{i+1}) adjacent positions, as shown in Fig. 1. Beamforming networks as those based in the Butler matrix allow the simultaneous measurements of all three beams; however, when a different beamformer is used the measurements of the three beams must be done in a sequential order. In this case, switching times in the range of microseconds will be needed to ensure that the three measurements are done within the channel coherence time, but these values are easily achievable by currently state-of-the-art devices.

The proposed tracking d-estimator is defined as

$$d=(P_{i+1}-P_{i-1})/P_i \quad (1)$$

where i=1,..,N, being N the number of beams. This estimator is, by definition, independent on the distance between the MT and the BS. For $d \approx 0$ the MT is moving within the current beam. An increasing positive value means that the MT is moving towards the i+1 beam, whilst a negative value means the MT moves backwards to the i-1 beam. The –3dB beamwidth of the three beams must be the same as well as the angular range between the directions of maximum gain of adjacent beams, $\Delta\phi$, to achieve the optimum performance [6]. Under this assumption, a threshold value of ±1 can be used for a first decision to select the activated beam. However, using the tracking d-estimator, a more accurate DOA estimation is obtained from (2) which was obtained heuristically and where ϕ^i_{max} is the direction of maximum gain of the central beam.

$$\hat{\phi}_{DOA} = \begin{cases} \phi^i_{max} - (1/d+2)\cdot(\Delta\phi/2), & d<-1 \\ \phi^i_{max} + d\cdot(\Delta\phi/2), & |d|<1 \\ \phi^i_{max} - (1/d-2)\cdot(\Delta\phi/2), & d>1 \end{cases} \quad (2)$$

The signal used for DOA estimation can be based on a training sequence of constant power or on a pilot tone of lower frequency modulated on the carrier frequency.

III. Simulation Results

Fig. 2 shows the tracking and DOA estimation algorithm performance obtained by means of simulation with $\Delta\phi$=22.5 and $\Delta\phi_{-3dB}$=28 degrees and for a MT with a random movement. It may be seen how the tracking d-estimator is near ±1 when the MT is near the edge of a sub-sector (shown with a horizontal dashed line). The sharp change of the tracking d-estimator corresponds to a handover between sub-sectors, which implies a change into the beam position used to cover the MT. Also DOA estimation performance is depicted. The DOA estimation error is not constant and changes depending on the MT position, but it can be observed that the error is always lower than the maximum error that it is 1.93-degree for $\Delta\phi$=22.5 and $\Delta\phi_{-3dB}$=28 degrees [6].

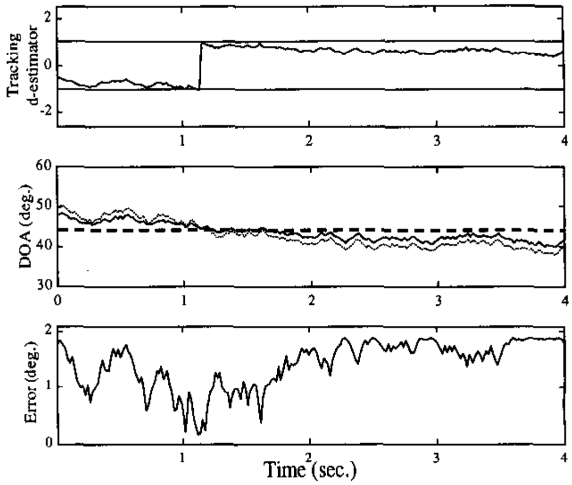

Fig. 2. Tracking and DOA estimation algorithm performance for a MT with random movement in a 4-beams scenario ($\Delta\phi$=22.5-degree) and $\Delta\phi_{-3dB}$=28-degree. In the DOA subplot the dashed trace shows the estimated angle while the solid trace shows the true angle. The horizontal dashed line shows the boundary between adjacent sub-sectors.

Furthermore, the influence of multipath on the DOA estimation error was investigated by means of simulations. The results were obtained taken into account the geometrically based single bounce elliptical channel model [3]. The mean ($\bar{e}$) and standard deviation (σ_e) of the DOA estimation error is shown in Tab. 1 as a function of the ensemble average angle spread (σ_ϕ) and taken into account that there are five multipath components. The results shown in Tab. 1 are for $\Delta\phi_{-3dB}$= 28-degree (4-beams scenario). A two-path loss exponent and the worst case scenario where each scatter is assumed to be a perfect reflector with a reflection coefficient of 1 have been assumed. Simulation results indicate that for the worst case (σ_ϕ=10 degrees), $\bar{e}$ only increases 0.3604 degree respect to the ideal (no multipath) case. It can also be observed that σ_e does not degrade drastically respect to the no multipath case and high DOA estimation errors were seldom detected during the simulations. The DOA estimation error increases when the number of multipath components increases but we can conclude that the mean error does not degrade more than 1-degreee when fewer multipath components appear, as expected in 60 GHz LOS indoor channels [7].

TABLE I
INFLUENCE OF MULTIPATH ON DOA ESTIMATION ERROR

σ_ϕ(deg.)	$\bar{e}$	σ_e
0	1.0389	0.5471
10	1.3996	1.5134
25	1.3661	1.4008
45	1.3323	1.3324
90	1.1243	1.1243

IV. EXPERIMENTAL RESULTS

The algorithm has been tested experimentally and the results compared with simulations. The measurement set up is depicted in Fig. 3. The measurements were carried out in an indoor environment. An unmodulated narrow band pilot tone is up-converted to the 60 GHz band and transmitted by a transmit antenna (horn antenna). The horn antenna is installed on a pole and aligned to the receiver antenna. It can be moved in the azimuth angle continuously.

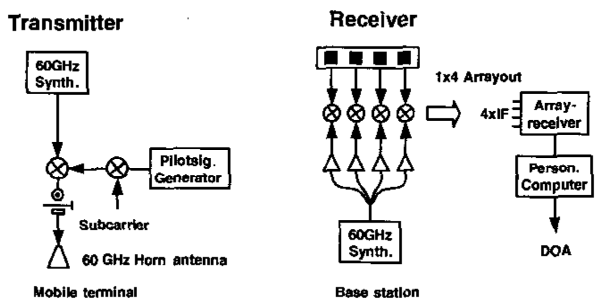

Fig. 3. Schematic of the experimental set-up.

After receiving the transmitted signal at the 60 GHz array antenna [9], the received signals pass the 60 GHz RF-front end, which consists of a local oscillator, a distribution network comprising 60 GHz power amplifiers and mixers. The received RF signals are down-converted into the intermediate frequency (IF) band at 200 MHz. The digital unit in the receiver converts the preamplified IF signals into the base band signals using a quadrature mixer (IQ down converter). After base band conversion, the signals are filtered by analogue low pass filters with a cut off frequency of 2.5 MHz. The signals are digitized by a sampling frequency of 16 MHz and transferred into a PC for further processing. From the four digital signals, the powers of the three adjacent discrete directions (P_{i-1},P_i, and P_{i+1}) are calculated by means of the delay and sum algorithm [3]. Hence, the three calculated powers are used for the proposed algorithm applying (1) and (2).

Although the algorithm is aimed for direct application to the RF signal, due to equipment limitations, its feasibility has been proven employing the digitized base band signals, the power information remaining unaltered. It should be noticed that the algorithm may be applied to high frequency wideband signals by measuring the signal power directly at the RF level avoiding the down-conversion to base-band and analog-to-digital (A/D) converters.

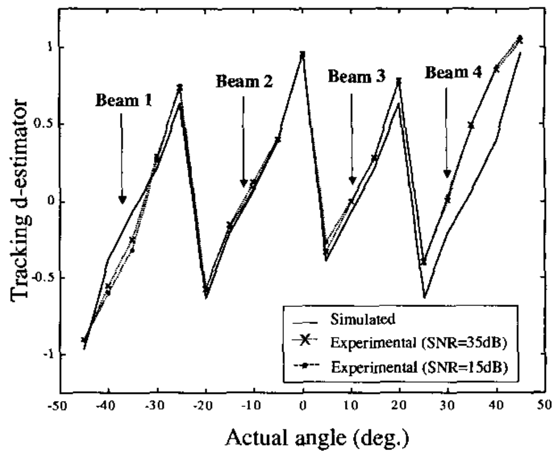

Fig. 4. Simulated and experimental tracking d-estimator as a function of the actual angle.

A set of four beams has been considered, so that $\Delta\phi$ is equal to 22.5 degrees for a 90 degrees sector. Simulation results indicated that the maximum DOA estimation error for this case would be 1.93 degrees; although DOA estimation errors lower than 1 degrees could be achieved by increasing the number of beams [6]. Fig. 4 depicts the simulated and experimental tracking d-estimator as a function of the actual angle. An angle range between –45 and 45 degrees with steps of 5 degrees has been considered. As stated previously, the sharp change of the tracking d-estimator corresponds to a switch of the activated beam employed to cover the MT (central beam of the algorithm).

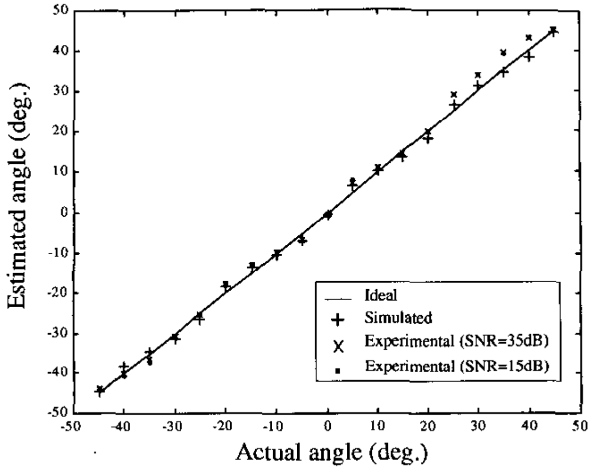

Fig. 5. Simulated and experimental DOA estimated angle versus the actual angle. The solid line depicts the ideal estimation.

Fig. 5 shows the simulated and experimentally estimated DOA angles versus the actual angles. From both, Fig. 4 and Fig. 5, it may be stated that the simulated values agree quite well with the experimental values differing slightly at angles far away from the broadside directions. This degradation is due to the fact that the array calibration was carried out only at the broadside direction (0 degrees). The DOA estimation performance may be further improved by calibrating the antenna array over all azimuth angles reducing the array offset errors and the different amplification and phase shifts of the individual antenna signals.

V. CONCLUSION

The feasibility of a novel DOA estimation algorithm for switched-beam antenna systems has been demonstrated. Experimental results, carried out at 60 GHz, agree quite well with the simulated results. The proposed algorithm is suitable for real-time beamforming broadband applications operating in the mm-wave band as fast DOA estimations with reduced complexity and no convergence time are achieved.

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