Experimental Verification of the Hybrid Smart Antenna Algorithm With Modulated Waveforms

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Abstract—The hybrid smart antenna approach utilizes a subset of array elements selected according to the receive signal strengths to perform beamforming, thus improving the computational efficiency, and reducing the hardware implementation cost. The previous implementations and published experimental results of this algorithm have been based on continuous-wave (CW) transmit signals, and without modulation. In order to verify the operation of the hybrid smart antenna algorithm with modulated waveforms, the developed 2.4- and 60-GHz testbeds are modified to generate and receive data modulated waveforms. The modifications also include the use of preamble bits at the beginning of each data frame transmitted, and implementation of a sliding window correlator at the receiver to synchronize with the data frames. Binary phase shift keying (BPSK) modulation is used with a 1 megabit per second (Mb/s) data rate for information transfer. The obtained beam patterns agree well with the theoretical results thus verifying the developed hybrid smart antenna algorithm.

Index Terms—60 GHz, adaptive smart-antennas, beamforming, hybrid smart-antennas, low-cost antenna array, modulation, wireless communications.

I. INTRODUCTION

SMART antenna systems utilize multiple antennas and adaptively steer their beam patterns to increase the antenna gain, and reduce multipath fading [1], [2]. Moreover, depending on the number of elements on the array, several nulls in the beam pattern can be formed corresponding to the interferer locations. These features of the smart antenna systems, consequently increase system capacity, extend communication range, and reduce bit error rates.

Although the performance of the smart antenna systems increase by the number of elements on the array, additional costs arising due to the RF hardware requirements, and computational complexity limit the possible number of elements. For instance, the computational requirements of the adaptive weight calculation algorithm increase exponentially with the number of array elements, thus, driving the computational time of the system up (ON² for the very popular least means squares algorithm where N is the number of array elements), and increasing the tracking delay [1]. To avoid these limitations and high costs, antenna switching is proposed in the literature as an alternative [1]. Antenna switching employs several directional antennas and selects the antenna with the highest received signal power. This system has very low computational complexity, and relatively low hardware cost, however it suffers from scalloping effects and its angular resolution is limited.

Taking into account these advantages and limitations, our group proposed a hybrid smart antenna system that combines the advantages of the adaptive smart antenna and the antenna switching approaches [3]. This system employs an array of directional elements arranged in a linear geometry but each tilted at a different angle with respect to the array axis. The tilt angles are optimized to yield the best performance with minimal scalloping effects [4]. The algorithm selects the subset of the array elements with the highest total receive signal power for the beamforming stage significantly reducing the computational complexity. The performance of the proposed hybrid smart antenna system was evaluated by computer simulations in [5] and experimentally in [6], [7], and [8]. In [8], it was also shown that for a 60-GHz system, the cost savings due to use of a hybrid smart antenna system is very significant because of very high RF component prices.

All the previously mentioned experimental verification of the hybrid smart antenna algorithm have been conducted using a continuous--wave (CW) signal at the transmitter, thus, eliminating the need for Tx-Rx synchronization. For upgrading the existing 2.4- and 60-GHz testbeds to handle modulated waveforms, however, a wireless synchronization mechanism has to be implemented. This letter briefly describes some of these modifications and presents the obtained experimental results both at 2.4 and 60 GHz.

The rest of the letter is organized as follows. In Section II, the adaptive weight update operation is briefly described. Section III describes the required modifications in the testbeds and their implementation. Section IV contains the experimental results and discussion of the obtained results. Section V concludes the letter.

II. PROBLEM FORMULATION

In this section, the weight update operation is briefly described, a detailed version is included in [7]. The transmitted signal \( d(t) \) coming from the direction \((\theta', \phi')\), impinges upon the antenna array, and it is assumed to be narrowband such that its complex envelope does not change through the array. This assumption requires that the total length of the array \( L \) should satisfy the following relation:

\[
L \ll cT_s
\]

(1)

where \( c \) is the speed of light and \( T_s \) is the symbol period.

If the received signal vector at the array is \( \mathbf{u}(t) \), the output of the beamformer is

\[
\hat{d}(t) = \mathbf{w}^H(t) \mathbf{u}(t)
\]

(2)
where \( \mathbf{w} \) is the complex vector of beamforming weights, and subscript \( H \) stands for the Hermitian of the vector. The LMS algorithm updates these weights as follows:

\[
\mathbf{w}(t + \Delta t) = \mathbf{w}(t) + \mu e(t) \mathbf{u}(t) \tag{3}
\]

\[
e(t) = d(t) - \hat{d}(t) \tag{4}
\]

As seen in (3), the weights are updated according to the error between the system output and the desired signal and \( \mu \) adjusts the magnitude of the updates. The superscript * denotes the complex conjugate operation. The maximum value of \( \mu \) determined by the eigenvalues of the received signal’s autocorrelation matrix must not be exceeded in order to ensure convergence.

### III. MODIFICATIONS AND IMPLEMENTATION

As indicated in (4), the transmitted signal should be known at the receiver to initiate the weight update operation. For this purpose, the data is divided into 450 bit frames and a 50-bit preamble is added in front of each data frame. If the preamble is known at the receiver, the weight update can be possible during preamble transmissions. However, for this to happen, the receiver has to know the timing of the frames precisely so that it can enable the weight update operation requiring a synchronization mechanism.

In digital wireless receivers, the time recovery is usually established through the use of orthogonal waveforms [9]. An orthogonal waveform has a very high correlation with itself but negligible correlation with its time-shifted versions. As a result, timing of the orthogonal waveform can be fully recovered by employing a sliding correlator and detecting the peaks [9] and the accuracy depends on the correlation properties of the selected waveform. In [10], the authors studied and optimized bit-sequences of varying length in terms of their correlation properties. In this letter, the 50-bit preamble sequence “39911AE92BC3E” in hexadecimal format from [10] is selected as the preamble and tested to have good correlation properties. The rest of the frames are filled with random data bits. An Agilent E4438C vector signal generator programmed for the designed frame format with the selected preamble is used to generate the transmit waveform [11]. BPSK modulation with 1-Mb/sec data rate, and the two receive antennas receive exactly the same signal, there is no noise in the system so the weights are expected to converge to the same value of 0.5 and remain constant. However, with above 50% clipping, the variance of the magnitudes of weights becomes equal and larger than the variance of a random variable uniformly distributed between the interval [0, 0.5]. Therefore, caution must be exercised in designing the system, to minimize the nonlinear effects.

At the receiver, the correlation is continuously calculated and the data bits corresponding to preamble are used as the desired signal for the weight update whenever a correlation peak is found. To eliminate the synchronization errors due to the phase discrepancy between the Tx and Rx oscillators, a quadrature demodulator is employed.

### IV. EXPERIMENTAL RESULTS

In this section, the results of the 2.4- and 60-GHz testbeds will be presented, details of implementation and the calibration procedures are described in previous publications [6]–[8].

#### A. 2.4-GHz Testbed Results

As there is significant multipath and noise in this frequency bands, the experiments are conducted inside an anechoic chamber in order to obtain meaningful beam patterns. The computer handling the A/D conversion and beamforming
operations is controlled from outside the chamber by a remote
desktop connection. A BSPK modulated signal with 2.4-GHz
center frequency and 1-Mbps data rate is transmitted by a horn
antenna and the receiving array has 8 isotropic (sleeve antenna)
elements. The smart-antenna testbed downconverts the carrier
frequency to 5 MHz and then digitizes at 25 MSample/s by
an 8-channel analog-to-digital converter (ADC). In all of the
experiments, the elevation angle \( \theta \) is selected to be \( \pi/2 \) and the
azimuth angle \( \phi \) corresponding to the angle of arrival (AOA)
of the signal is calculated from the obtained combining weights
and compared to the actual AOA. The received bandpass signal
is converted to its low-pass equivalent by calculating its Hilbert
transform. Sliding window correlation operation is applied to
all the received signals and the most repeated peak position is
selected as the synchronization point to prevent errors due to
failure of receiver channels. As shown in Fig. 2, the correlation
peak locations coincide for all eight channels pointing out
perfect synchronization for all the receiver channels.

After ensuring that the synchronization mechanism works,
the calibration procedure described in [7] is completed and the
LMS weight vectors for several AOA are obtained. The beam
patterns corresponding to these weight vectors are then calcul-
ated assuming isotropic radiation patterns. In order to ensure
that the sampling rate is sufficiently high to prevent sampling
phase errors, the received data is interpolated by 10. In this case
the LMS errors for all angle of arrivals turn out to be on the order
of \( 10^{-5} \), indicating a good convergence of the weights.

In order to check if the system works as expected, the system
is first configured as a typical smart antenna system using all
the eight receiver channels. In Fig. 3, the beam patterns corre-
sponding to AOA = 60°, AOA = 75°, and AOA = 90° cases
are plotted, and it is seen that the system is able to accurately
steer its receive beam in the signal direction.

As aforementioned, hybrid beamforming algorithm reduces
the complexity of the beamforming operation by selecting a
subset of the elements on the array. The beam pattern cor-
sponding to different number of selected array elements is
shown in Fig. 4 for AOA = 60°. As expected, slightly higher
sidelobes and wider main lobes are observed as the number of
selected elements is reduced, thus, agreeing with the previous
results obtained using CW signals [6]–[8]. The proposed hybrid
smart antenna system was, thus, able to determine the correct
AOA for modulated signal even with only three antennas
selected and the maximum sidelobe level does not exceed
\(-10\) dB.

B. 60–GHz Testbed Results

The test procedure applied here is very similar to the one ex-
plained in [8]. Agilent E4438C signal generator is set to generate
a BPSK signal with 1-GHz center frequency and this signal is
mixed with a 59-GHz sine wave to obtain the 60-GHz modu-
lated signal. The transmit horn antenna is located 50 cm from the
receiver, and the receive horn antennas are spaced 5.1 cm apart.
To establish significant beam overlapping, one of the antennas
is tilted 12° with respect to the array axis, so that its radiation
pattern peak points to 78° as opposed to 90° as shown in Fig. 5.
Fig. 5. Measurement setup for the 60-GHz experiments. Please note that the peaks of the element radiation patterns are directed to different angles (78° versus 90°) to ensure significant radiation pattern overlap.

Fig. 6. Theoretical and measured phase differences.

The signal format and the synchronization mechanism are the same as the 2.4 GHz case, only difference being the bandpass filter centered around 5 MHz to eliminate the harmonics due to nonideal characteristics of the 60-GHz mixers.

For verifying the correct operation of the system, the estimated phase differences between the signals and the theoretical phase difference is calculated and plotted in Fig. 6. Due to large spacing of the array elements compared to the wavelength, and weak signal levels resulting from narrow antenna beamwidths, the phase difference changes rapidly and one can observe large deviations with the increase of scan angle from the calibration center, 95°. Fig. 7 demonstrates the resulting beam pattern for various AOA, for which the system was able to steer the beam peak to the desired location. The other two peaks in each of the radiation patterns are due to large spacing of the array elements and are called the grating lobes [1]. For the angular range of 93° to 97°, the beam peak is indeed at the transmitter direction, and its normalized power is larger than the grating lobes.

V. CONCLUSION

In this letter, the experimental results of two smart-antenna testbeds employing the hybrid beamforming algorithm proposed in [3] are presented. The preamble added to the transmitted data frames is used to establish synchronization, as well as to help the receiver generate a local replica of the transmitted signal for weight calculation operation.

The results obtained using modulated data are consistent with simulation results given in [5] and experimental results given in [6]–[8] and suggest that a hybrid beamforming algorithm is a promising method for decreasing hardware related costs, as well as computational complexity and thus resulting in a higher tracking speed. The experimental results show in all cases that, the smart-antenna prototypes are able to determine the correct angle of arrival and steer the beam to the transmitter direction.

REFERENCES