DVB-S Signal Tracking Techniques for Mobile Phased Arrays

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Abstract—A system that uses adaptive beamforming techniques for mobile Digital Video Broadcasting Satellite (DVB-S) reception is proposed in this paper. The purpose is to enable DVB-S reception in moving vehicles. Phased arrays are able to electronically track the desired signal during dynamic behaviour of the vehicle the array is mounted on.

The proposed system uses blind beamforming to adapt the array steering vector to changing signal (conditions and) directions. Movement of the vehicle, the phased array is mounted on, leads to modulus and phase deviations at the beamformer output. An extended version of the Constant Modulus Algorithm (CMA) algorithm is used to adapt the steering vector weights to compensate for those deviations.

For simulation of the proposed system a model of vehicle dynamics is used to generate realistic antenna data. Simulation of the proposed system based on this antenna data shows appropriate corrections for modulus and phase deviations.

I. INTRODUCTION

Digital Video Broadcasting Satellite (DVB-S) [1] signals originate from geostationary sources and are usually received by parabolic antennas. A moving parabolic antenna, for example on top of a vehicle, constantly needs mechanical realignment. The parabolic antenna can be replaced by a phased array antenna that electronically tracks the desired signal by means of adaptive beamforming techniques. The main objective of this work is to integrate adaptive phased array techniques in the traditional DVB-S receiver chain to support tracking of the desired DVB-S signal in a mobile environment.

DVB-S uses Quadrature Phase-Shift Keying (QPSK) modulation for mapping digital inputs to waveforms. QPSK conveys information by phase modulation of the carrier output signal. Structural properties of QPSK modulated signals are used by the adaptive beamformer to track the Direction of Arrival (DOA) of the desired signal.

Since a DVB-S signal guarantees the narrowband assumption, a phase shift of an antenna signal acts like a shift of that signal in time [2]. The term narrowband is used for signals whose bandwidth is much smaller than their center frequency (generally 1% or less) [2]. The proposed system uses phase shift based beamforming to guarantee coherent summation of the antenna data. The phased array type used in this paper is a Uniform Linear Array (ULA) of $N$ antenna elements.

The output of the ULA at one time instant is a vector of $N$ quadrature samples coming from the analog antenna front-ends and is indicated by $x$. Those quadrature samples are input to an adaptive beamformer. A general form of such a beamformer can be seen in Figure 1.

Movement of a phased array introduces modulus and phase deviations in the QPSK modulated output of the beamformer due to angular mispointing and the Doppler effect, respectively. Those effects are described in Section III-A and III-B. The adaptive array algorithm compensates for those deviations by altering the steering vector weights of the beamformer. The beamformer output and the steering vector weights are indicated by $y$ and $\phi$, respectively (see Figure 1). The adaptive array algorithm employed in this work belongs to the class of blind beamforming algorithms and is based on the traditional Constant Modulus Algorithm (CMA) [3] with an extension to its cost function [4]. A description of this extended form of CMA can be found in Section III-C. Integration of this adaptive array algorithm in the DVB-S receiver chain is explained in Section IV.

Section V describes simulation results of the proposed system based on realistic antenna data. This data incorporates the effects of vehicle dynamics on the signals received by the separate antenna elements of the array. The vehicle dynamics are modeled using the planar bicycle model [5].

An analysis of the computational complexity of the extended CMA update operation is given in Section VI. A discussion of the results can be found in Section VII.

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II. RELATED WORK

The use of phased array antennas for reception and tracking of satellite signals has been investigated in for example [6], [7] and [8]. Much of the existing work is based on techniques other than the blind beamforming method applied in this paper.

A frequently used signal tracking technique is the squint beam tracking algorithm which incorporates two levels of phase shifters [6]. One level of phase shifters generates the main beam for the actual reception of the satellite signal, whereas the other level generates a second beam close to the first beam. This second beam, called the squint beam, rotates around the main beam. Signal strengths received by the squint beam are used to steer the main beam.

The work of Chiba in [9] describes a digital beamforming system that applies Beam Space Constant Modulus Algorithm (BSCMA) techniques for adaptive steering. BSCMA is a version of CMA with a reduced number of steering vector weights being optimized during the CMA convergence. Basically, first multiple beams are formed by executing a Fast Fourier Transform (FFT) on the antenna data. Thereafter, only the weights of beams with a certain minimum signal strength are selected for optimization by the CMA loop [9].

Traditionally, phase offsets in the beamformer output, caused by the Doppler effect, are corrected in the derotator of the QPSK demodulator [10]. Such a derotator is often implemented by a Digital Delay Locked Loop (DDLL) or a Phase Locked Loop (PLL), which results in complicated structures, long convergence times and large signal degradation [11].

No studies have been performed on the feasibility and computational complexity of CMA with the extended cost function of Xu [4] for blind beamforming of DVB-S signals. The latter approach is accounted for in this paper and enables direct correction (in the beamformer) of phase offsets caused by the Doppler effect.

III. BLIND BEAMFORMING OF DVB-S SIGNALS

The next three Sections discuss phase and modulus deviations in the QPSK modulated beamformer output caused by phased array movement and the adaptive algorithm that enables correction of these deviations.

We assume that phaseshift corrections are performed in the digital domain, since today’s high-speed integrated circuitry are able to cope with the large bandwidths required for DVB-S.

A. Phase deviations

A ULA mounted on a moving vehicle experiences both translational and rotational movement. In the case of translational movement all separate antenna elements experience the same change in signal path length. Equal changes in path length result in equal phase shifts of the narrowband signals received by the antenna elements.

The Doppler phase shift $\varphi_D$ (in radians) for an antenna moving with a velocity $v$ (in meters per second) towards the transmitter during a certain time period $T$ (in seconds) can be found by:

$$\varphi_D = \int_0^T \frac{2\pi}{\lambda} v(t) dt$$

Herein, $\lambda$ is the wavelength of the received signal in meters.

Beamforming can be written as $y = \phi^H x$ [2]. An identical Doppler phase shift $\varphi_D$ applied to all quadrature antenna samples $x$ results in a phaseshift $\varphi_D$ of the beamformer output $y$, this can be shown as follows:

$$y_{\varphi_D} = \phi^H (xe^{j\varphi_D}) = (\phi^H x)e^{j\varphi_D}$$

Herein, $y_{\varphi_D}$ is the beamformer output containing the phase offset caused by the Doppler effect.

QPSK uses four different phases to represent transmitted information. Those phases are equally distributed on the unit circle of the IQ plane. Each of these four phases represents a symbol and each symbol represents two bits of data. The positions of these symbols are generally drawn in a so-called constellation diagram.

Translational movement of the array leads to a phase offset in the beamformer output. This phase offset translates to a rotation of the received QPSK symbols from their original position in the QPSK constellation.

B. Modulus deviations

Rotational movement of the ULA influences the DOA angle. The array transfer $S_a(\theta)$ of an $N$-element ULA with uniform spacing and isotropic elements can be written as:

$$S_a(\theta) = \sum_{n=1}^{N} e^{j2\pi \frac{\sin(\theta)}{\lambda} (n-\frac{N+1}{2})}$$

Herein, $\theta$ represents the DOA angle, $d$ the distance between two adjacent elements and $\lambda$ the wavelength of the received signal. The phase reference of this array transfer function is assumed to be in the center of the array. The negative (for $n = \lfloor \frac{N}{2} \rfloor$) and positive (for $n = \lceil \frac{N}{2} \rceil$) complex exponentials are similar in size and this nullifies their net phase effect. Therefore, the phase shift introduced by the beamformer in the case of rotational movement is zero.

Rotational movement of the ULA at all times affects the gain transfer of the ULA. This gain transfer is generally called the array factor [12]. The gain decrease can be recognized in the modulus decrease of the received QPSK symbols from their original modulus in the QPSK constellation.

C. Extended CMA

Phase and modulus deviations in the QPSK modulated beamformer output need to be corrected before the demodulator. These deviations can be compensated by altering the steering vector weights $\phi$ of the beamformer.

Traditional CMA [3] adjusts steering vector weights based only on modulus effects in the beamformer output caused by mispointing. CMA is based on a cost function and gradient...
descent methods to decrease costs. The cost function of traditional CMA is defined as the expected deviation of the squared modulus of the beamformer output with respect to a constant value. For a normalized QPSK modulated beamformer output this constant value is one, since the QPSK symbols lie on the unit circle. Based on the notation of Figure 1, the CMA cost function can be written as [13]:

$$J_{\text{CMA}}(\phi) = E(|y|^2 - 1)^2 = E(|\phi^H x|^2 - 1)^2$$

(5)

Herein, ‘E’ represents expectation. The aim of CMA is to minimize $J_{\text{CMA}}(\phi)$ by altering the steering vector $\phi$. Lower costs indicates less deviation from the constant modulus.

CMA for QPSK based receivers can be improved by adjusting the weights based on both modulus and phase deviations. The equal phase distribution of a QPSK modulated signal can mathematically be expressed by $\sin(2y_x) = 0$, herein $y_x$ represents the instantaneous phase angle $\varphi$ of $y$. This expression is used by Xu [4] to derive a new cost function $J_{\text{CMAX}}$ based on both modulus and phase deviations in the beamformer output:

$$J_{\text{CMAX}} = E\left(|y|^2 - 1\right)^2 + E\left(\sin^2\left(2y_x\right)\right)$$

(6)

The cost function $J_{\text{CMAX}}$ is illustrated in Figure 2. Herein, the x-axis shows the real part of the beamformer output $y$, the y-axis shows the imaginary part of $y$ and the z-axis shows the corresponding costs $J$. Minimum costs are reached whenever $y$ simultaneously has a unit modulus and a phase equal to one of the QPSK symbol phases.

Both $y$ and $y_x$ in $J_{\text{CMAX}}$ can be rewritten in terms of $\phi$ and $x$:

$$J(\phi)_{\text{CMAX}} = E\left(|\phi^H x|^2 - 1\right)^2 + E\left(\sin^2\left(2\cdot \text{arctan}\left(\frac{\phi^H x - x^H \phi}{j \phi^H x + x^H \phi}\right)\right)\right)$$

(7)

Similar to the traditional version of CMA the costs $J_{\text{CMAX}}$ are iteratively minimized using a stochastic gradient-descent. The steering vector $\phi$ is updated in the direction of the negative gradient to minimize $J$. Mathematically, this can be written as [3]:

$$\phi[n+1] = \phi[n] - \mu \nabla \varphi J$$

(8)

Herein, $\mu$ determines the convergence rate of the gradient descent. The steering vector update equation of extended CMA can now be found by using the gradient $\nabla J_{\text{CMAX}}$, derived in [4], in Equation 8:

$$\phi[n+1] = \phi[n] - \mu \cdot \frac{8j (|y|^4 - |y|^2) + 4 \sin(4y_x)}{4j \cdot y} \cdot x$$

(9)

IV. PROPOSED MOBILE DVB-S RECEIVER

The blind beamforming technique mentioned in the previous section is integrated in the DVB-S chain. After this integration the following mobile DVB-S receiver is obtained:

The adaptive array algorithm of the mobile DVB-S receiver implements the update equation of the extended version of CMA (Equation 9). This recurrence relation requires an antenna snapshot $x$ and the beamformer output $y$ corresponding to that particular antenna snapshot.

A Root-raised Cosine (RRC) matched filter is required at the receiver side to compensate for the effects of RRC pulse shaping at the sender to maximize the Signal-to-Noise Ratio (SNR) and lower the Intersymbol Interference (ISI). The output of the matched filter, indicated by $y_m$, is an upsampling reconstruction of the original QPSK data symbols.

The adaptive array algorithm uses the matched filtered and down-sampled beamformer output, indicated by $y_{m,\downarrow}$, as an input signal. The other input signal, the complex antenna data $x$, is delayed and down-sampled to synchronize with $y_{m,\downarrow}$. In Figure 3 this delayed and down-sampled complex antenna snapshot is indicated by $x_{d,\downarrow}$. The steering vector weights are updated at the same rate as $y_{m,\downarrow}$ and $x_{d,\downarrow}$.

V. SIMULATION RESULTS

Simulations of the mobile DVB-S receiver (Figure 3) are performed to gather conclusions on the actual behaviour of the proposed mobile DVB-S receiver for realistic antenna data. This data incorporates the effects of translational and rotational vehicle dynamics based on the planar bicycle model.

The planar bicycle model is a set of differential equations that can be used to analyse the dynamic behaviour of a vehicle during cornering. An extensive introduction to this model can be found in [5].

The simulations in this paper use a convergence rate $\mu$ of $5 \cdot 10^{-3}$. This particular rate leads to correct convergence in
all simulations performed in this work. An analytical analysis of the convergence behaviour of this extended type of CMA for different values of $\mu$ is out of the scope of this work.

A. Instantaneous steering angle scenario

The scenario for antenna data generation is based on the dynamics of a Renault Clio RL 1.1, with a ULA longitudinally mounted on its roof during an instantaneous steering angle. Vehicle characteristics for this type of car can be found in [14].

The simulation starts at $t = 0$ where the steering angle equals zero degrees ($\delta = 0^\circ$) and the car’s forward velocity is 72 km/h. Initially, the direction of the velocity vector of the vehicle is orthogonal to the DOA of the received satellite signal. At $t = 0.2$ seconds the steering angle is changed instantaneously to $11.5^\circ$. Such steering behaviour is also called a step steer input [5]. The instantaneous steering angle affects the rotational and translational movement of the vehicle. These types of motion lead to a Doppler phase error and mispointing, respectively.

1) Rotational movement: The instantaneous steering angle changes the yaw rate. Both the steering angle and yaw rate are shown in Figure 4. For the yaw rate, a second-order step response can be recognized. Herein, the overshoot depends on the velocity of the car in the initial situation. The constant yaw rate that will be reached depends on the magnitude of the instantaneous steering angle.

Initially, the DOA angle for the satellite signal received by the roof-mounted ULA is zero. This angle changes due to yawing motion of the vehicle, these changes can be seen the rightmost plot of Figure 4. Antenna data generation for performance testing of extended CMA incorporates these DOA deviations.

2) Translational movement: At $t = 0$, the direction of the velocity vector of the vehicle is orthogonal to the DOA of the received satellite signal. Therefore, the Doppler phase error of the satellite signal received by the roof-mounted ULA is zero at first.

The instantaneous steering angle leads to a non-zero velocity vector component in the direction of the source. The latter results in an increasing Doppler phase error. The magnitude of the velocity vector component pointing towards the source ($v_s$) and the cumulative phase error ($\phi_D$) of the received signal can be seen in Figure 5. Besides the DOA deviations the generated antenna data also incorporates phase errors.

B. Performance of extended CMA.

The performance of the CMA algorithm with extended cost function is evaluated based on antenna data generated during the instantaneous steering angle scenario. The simulated adaptive ULA consists of eight elements. Furthermore, Additive White Gaussian Noise (AWGN) causing 16 dB SNR is included in the channel model. A SNR of 16 dB corresponds to satellite signal reception in clean air [15].

Figure 6 shows multiple radiation patterns (stacked after each other). The figure visualizes the changes in array sensitivity over time when extended CMA is used during the instantaneous steering angle scenario. Based on these radiation patterns it can be concluded that the extended CMA algorithm is able to update the steering vector weights in such a manner that the array is highly sensitive in the reference direction. Recall that the reference direction during the instantaneous steering scenario can be seen in Figure 4 (see DOA angle).

Fig. 4. Yaw rate and DOA during the steering manoeuvre.

Fig. 5. Velocity $v_s$ and phase error during the steering manoeuvre.

Fig. 6. Radiation patterns (over time) during the instantaneous steering angle.
Figure 6 is unsuitable to analyze the Doppler phase error correction performance of extended CMA. A more common and accurate expression for the performance of a communication channel is the Bit Error Rate (BER). Bit errors can be caused by distinct phase and modulus deviations or a combination of both.

The running BER for CMA with the extended cost function during the instantaneous steering simulation is below the required 2·10⁻⁴, which implies correct adaptive steering and Doppler adjustments. The traditional CMA algorithm does not incorporate Doppler phase corrections. Therefore, simulation with this algorithm results in a running BER of 0.5.

VI. COMPUTATIONAL COMPLEXITY ANALYSIS

A short analysis on the computational complexity of extended CMA is given to gather insight on the scalability of the extended CMA algorithm for arrays with a large number of elements. The number of antenna elements required for a practical implementation of a DVB-S beamformer is in the order of hundreds of antenna elements [8].

Analysis of the computational complexity requires the update operation (Equation 9) to be split in basic arithmetic operations. These basic operations can be seen in Figure 7. Herein, y[k − 1] and x[k − 1] are the previous complex beamformer output and complex antenna snapshot, respectively. Note, that n instead of k is used to index steering vector updates. This is done to indicate that the rate of steering vector updates may differ from the beamformer sample rate. Typically, the update rate of n can be in the order of hundreds times smaller than the sample rate k.

![Block diagram of the extended CMA algorithm.](image)

An expression for the computational complexity of the extended CMA algorithm can be found by counting the required operations for a steering vector update. In Figure 7 one can recognize (N + 1) complex multiplications per steering vector update. Herein, N is the number of antenna elements. The number of other required operations is not affected by an increase of N. Thus, the computational complexity of extended CMA grows linearly with N.

VII. CONCLUSION

Extended CMA can be integrated in the DVB-S receiver chain to provide blind adaptive steering for a ULA mounted on a moving vehicle. The algorithm calculates steering vector adjustments to correct both phase and modulus deviations in the beamformer output. Simulations are performed with antenna data that incorporates the effects of realistic translational and rotational movement of the vehicle the ULA is mounted on. During these simulations extended CMA algorithm updates the steering vector weights in such a manner that the array is highly sensitive in the reference direction.

Traditionally, phase effects caused by translational array movement are corrected in the derotator of the QPSK demodulator. Application of extended CMA enables direct correction of Doppler phase offsets, which ceases the need for a separate derotator.

Additionally, it was shown that the complexity of extended CMA grows linearly with the number of antenna elements.

VIII. FUTURE WORK

Further research should confirm applicability of the algorithm for planar arrays. Currently, extended CMA is being implemented on a multi-core platform within our group.

REFERENCES