Doppler Compensation and Beamforming in OFDM based Aeronautical Communication using Direction of Arrival by MUSIC algorithm

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ABSTRACT
Aeronautical communication scenario consists of takeoff/arrival, en-route and taxi/parking conditions. Aircraft to ground communication comes under the en-route channel. Due to the mobile aeronautical communication, the system performance will be degraded by fading, Doppler frequency shifts etc. High velocity of the aircraft in the two ray en-route channel causes Doppler shift in the signal. To compensate effects of fading and Doppler shifts, a multi antenna based receiving scheme is proposed. The Doppler shifts are estimated from the arriving angle or Direction Of Arrival (DOA) of the signals at the receiving antenna. The LOS and reflected signal will be arriving at two different angles at the receiver. The Direction Of Arrival (DOA) for coherent sources are estimated using Smooth MUSIC algorithm. Based on the DOA, two sets of optimal antenna weights are generated for Linearly Constrained Minimum Variance (LCMV) beamforming. The signals are spatially separated by LCMV beamforming Doppler compensated and the best signal is selected by selection combining to improve the system performance.

Key Words: OFDM, Rician Channel, DOA, LCMV, Beamforming, Smooth MUSIC, Aeronautical Communication System

INTRODUCTION:
Aeronautical communication system provides various services for ground networks and high data rate in-flight connectivity. The aircraft to ground communication occurs when the aircraft is the transmitter and ground station is the receiver. Different aeronautical channels scenarios are introduced by different conditions during the flight of an aircraft. They include en-route scenario which means the aircraft is airborne, arrival/takeoff scenario and taxi/parking scenario.

Among the different techniques used for spectral efficient encoding, Orthogonal Frequency Division Multiplexing (OFDM) is one of the leading techniques. In addition to spectral efficiency, OFDM offers robustness against multipath channel impairment [4]. OFDM breaks the bandwidth into smaller bandwidths, which can then be encoded by modulation schemes such as QPSK, QAM etc. In OFDM, the subcarriers used are orthogonal to each other thereby preventing interference between the closely spaced carriers. OFDM also offers robustness against multipath channel impairment [3].

The air to ground communication channel can be modeled as a two ray Rician channel with a strong Line Of Sight (LOS) component and a reflected component. Both signals will be affected by fading, Doppler shifts and path loss.). The Doppler shifts can cause Inter Carrier Interference (ICI) in the received OFDM signal. At the receiving antenna both the signals will be arriving at two different angles called Direction Of Arrival (DOA). Thus to increase the diversity, a multiple receiving antenna scheme should be used. In multipath environments, multi-antenna technique can improve the performance of the communication system and it has become a research area in recent years. For the single-antenna system, existing methods to use in multipath channel is mainly the channel equalization procedure [4]. In this method, specific pilot signals will be inserted when sending the OFDM symbol. To interpolate channel estimates both in time and frequency, the pilot spacing has to fulfill the Nyquist sampling theorem. Maximum Likelihood (ML) estimation is a conventional method for frequency offset estimation proposed by Moose[5]. The frequency offset is first statistically estimated using maximum likelihood algorithm and is canceled at the receiver. This method is accurate but not bandwidth efficient.

Doppler shifts occurring are related to the angle between the direction of moving aircraft and the ground station. Thus by estimating the Direction Of Arrival (DOA) of the signals at the receiver, Doppler shifts can be estimated. DOA estimation algorithms can be classified as...
conventional and statistically optimum or Eigen based methods. Conventional method or Bartlett method uses a rectangular window of uniform weighting. Its main idea is to make all arrays in certain time to estimate a certain direction to measure the output power. Subspace based DOA estimation is based on the eigen decomposition of the received signal covariance matrix. Multiple Signal Classification (MUSIC) is a subspace based (eigen based) DOA estimation method which uses the properties of the covariance matrix and it is of high resolution. [6-8]. Based on the DOA, the signals are separated by beamforming. A beamformer performs a form of spatial filtering which separate each signal arriving at the array of sensors by choosing the beamformer weights. Common beamforming algorithms include classical beamforming and statistically optimum beamforming. Linearly Constrained Minimum Variance (LCMV) can be used to obtain optimal antenna weights for separating the signals. After beamforming the two signals have to be combined at the receiver to improve the system performance. Various multipath combining schemes include selection combining, maximal ratio combining and equal gain combining. Selection combining is used here since the number of receiving paths is less[11].

Figure 1: Aeronautical Channel

1. METHODOLOGY:

Figure 2 shows the basic block diagram of the proposed method. The aeronautical communication system employed is considered to be using Orthogonal Frequency Division (OFDM) system. The receiver consists of an antenna array composed of M receiving antennas on the ground station. Dual Doppler shifts occur in the en-route aeronautical channel due to the Line Of Sight ray and the reflected signal. The Doppler shifts are found by estimating the Direction Of Arrival (DOA) by Smooth MUSIC algorithm. Based on the DOAs, the signals are spatially separated, Doppler compensated in the time domain. The Doppler compensated signals are combined at the receiver by selection combining to improve the system performance.

A. OFDM Transmitter (Aircraft):
Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation technique for high speed data transmission in mobile communications. In OFDM, the subcarriers used are orthogonal to each other thereby
preventing interference between the closely spaced carriers.

B. Rician channel:

Aeronautical channel scenario can be divided into three: takeoff/landing, en route, and taxiing/parked. During the en-route scenario, the channel is considered as a two ray Rician channel with a strong Line Of Sight (LOS) and a reflected component. Each ray in the two ray channel will experience different Doppler shifts. The channel transfer function can be modeled as

\[ h(n, l) = \sum_{l=0}^{N} h_l \delta(n - \tau) \]  

where \( h_0 \) is the amplitude of the LOS path, \( h_1 \) is the amplitude of the reflected path, and \( \tau \) is the time delay assuming the receiver is synchronized to the first path.

C. Receiver (Ground Station):

Both LOS and reflected signal at the receiving antenna will be arriving at different angles at the receiving antennas denoted by their corresponding Direction Of Arrivals (DOA). Thus the two arriving signals are characterized with DOAs \( \theta_0 \) and \( \theta_1 \), time delay \( \tau \) and attenuation factors \( h_0 \) and \( h_1 \) respectively. Also they will be affected by the array response of the antenna after passing through the antenna array. The receiving antenna system considered as a Uniform Linear Array (ULA). The antenna array consists of \( M \) antenna elements and when the same signal reaches different antenna elements a phase difference between the sensor elements occurs. The output signal of the \( M \) element receiver antenna array can be represented in matrix form as \( X \).

\[ X = AS + N \]  

where \( A \) is the antenna array factor, \( S \) is the incident signal and \( N \) is the noise matrix.

D. DOA estimation using MUSIC algorithm:

Before DOA estimation, a spatial smoothing technique is used which divides the antenna array into several sub-arrays is used. Direction of Arrival (DOA) is the angle between the antenna array element and the directional vector of the arriving signal. Multiple Signal Classification (MUSIC) is a subspace method for DOA estimation. Subspace based DOA estimation method is based on the eigen decomposition of the covariance matrix of the received signal \( X \). These methods depend on two properties of the array covariance matrix \( R_x \). First one is that the expansion space spanned by eigenvectors of \( R_x \) can be partitioned into two subspaces; the signal subspace and the noise subspace. Second is that the direction vector from the signal source is orthogonal to the noise subspace. Thus the DOA estimator computes the DOA for the two paths.

\[ P_{MU}(\theta) = \frac{1}{a^H(\theta)E_nE_n^H a(\theta)} \]  

where \( E_n \) is the noise eigen vector matrix and \( a(\theta) \) is the steering vector.

E. Doppler shift estimation:

Doppler shifts are related to the angle between the transmitter and the receiving antenna assuming the relative velocity between the transmitter and receiver being constant for all the multipath signals

\[ f_{d,l} = \frac{f_C}{c} \cos(\theta_l) \]  

where \( f_C \) is the carrier frequency, and \( \theta \) denotes the angle between the direction of the moving aircraft and the receiver at the ground station.

F. LCMV Beamforming:

The Line Of Sight (LOS) and the reflected signal arriving at the antenna sensors have to be separated based on their Direction Of Arrivals (DOA) for compensating the Doppler shifts individually. A beamformer performs a form of spatial filtering which separates the signals according to the direction of propagation or direction of arrival. The beamformed signal for the \( l^{th} \) path will be

\[ y_{n,l}(n) = \sum_{m=0}^{M-1} x_m(n) w_{m,l} \]  

for \( l = 0; 1 \). Thus \( y_{n,l} \) is the output of the signal spatially processed through weights of \( M \) sensors for the arriving \( L \) paths. The weights of the beamformer are chosen based on Linearly Constrained Minimum Variance (LCMV) criterion. Using LCMV criterion, beamformer obtains the optimal beamforming vector of the \( i^{th} \) path signal. This criterion is to maintain the angle of the desired path gain under certain conditions so that the power of output signal is minimum. The analogous FIR filter has the weights chosen to minimize the filter output power subject to the constraint that the filter response to signals of frequency to be unity.

G. Doppler compensation:

Using the estimates of Doppler frequencies obtained from their corresponding DOAs, the Doppler frequency shifts are compensated for each path. After beamforming, two spatially processed signals will be available at the receiver. Of the two, the best signal is selected using selection combiner at the receiver. Here the signal with maximum power or signal to noise ratio is chosen. After selection combining, OFDM demodulation is performed for the best signal.

2. RESULTS:
Simulation parameters include OFDM using QPSK modulation, with a Rician channel power factor of 10 dB. The number of antenna arrays is chosen as 8. MUSIC algorithm is performed for SNR of 20 dB. The Direction of Arrival of the LOS and the reflected ray are estimated by MUSIC algorithm after spatial smoothing. Doppler shifts are estimated from DOA.

Figure 3 shows the LCMV beamformer power response with respect to DOA. Two sets of weights are generated for the LOS and reflected signal and the the LOS and reflected signals are spatially separated. Moreover, the BER performance is shown in figure 4 and it indicates that the error rate is reduced after Doppler compensation and combining.

3. CONCLUSION:
The Doppler shifts due to the line of sight and reflected signal in the OFDM based aeronautical communication system are estimated based on the Direction of Arrival. MUSIC algorithm after spatial smoothing the correlation matrix of the received signal provided accurate DOA estimates. Doppler shifts are estimated and compensated for each signal after beam forming. Since LCMV beam former is used, the spatial separation of the LOS and reflected signals based on DOA is found to be optimum. Simulation results show that the bit error rate of the OFDM based aeronautical communication system is reduced after Doppler compensation and selection combining.

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