SPATIAL DIVERSITY COMBINING USING BLIND ESTIMATION TECHNIQUES

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ABSTRACT

This paper proposes a spatial diversity combining approach by which spatially diverse telemetry signals from multiple antennas are combined before they are demodulated. The combined signal is guaranteed to at least replicate and in many cases improve upon the performance of any single antenna. By taking advantage of blind channel estimation, the combined signal can be computed as a time varying weighted sum of digital I and Q samples from multiple antennas. Multiple antenna combining is enabled by improved computation capability, high speed network connectivity, and accurate clock synchronization.

The algorithm will be demonstrated at the Reagan Test Site (RTS), whose modernization program encompasses multiple antenna sites with network capability and a state of the art software defined radio back end. This paper details the spatial diversity combining algorithm and discusses its merits and challenges.

Index Terms **-** Telemetry, Reagan Test Site, blind estimation, multiple antenna combining, best source selection, spatial diversity combining.

1. INTRODUCTION

Wireless communications channels can be subject to fading and signal dropouts due to multi-path effects or antenna motion [1]. This is a critical issue in aeronautical mobile telemetry (AMT) and current solutions include both polarization and spatial diversity combining. Telemetry ranges often employ multiple antennas and receive sites to ensure that signal reception is robust to channel fading, which can be common at a single site even with a polarization combiner in place. Historically, spatial diversity combining in the AMT community has been accomplished using a best source selector which performs either a post-detection digital or analog video combine of signals from multiple antennas [2].

In a post-detection digital combine, a single bit stream is selected based on a variety of signal strength and signal quality metrics. While this approach can be effective, selection criteria must be designed carefully, can be error prone, and performance is limited to the contributions of the single antenna with the highest signal-to-noise ratio (SNR).

In a typical analog combine, post-demodulated video signals are combined in a weighted sum. While some SNR improvements can be achieved with this approach, in practice achieving accurate timing synchronization between the various antenna sites can be challenging, particularly for widely separated antennas.

An alternative approach is to implement a pre-detection diversity combine that operates on complex I and Q samples of the down converted received RF signal. Blind channel estimation seeks to compensate for the effects of an unknown communications channel based on a received signal. In particular, blind beamforming seeks to determine the complex weights which optimize the SNR of a weighted combination of signals received at spatially diverse antenna locations [3][4].

In this paper we propose an approach by which these methods can be used to combine signals from multiple telemetry antennas. By first compensating for time and frequency offsets between antenna locations, then choosing optimal combining weights, it is possible to not only compensate for channel fading, but also improve SNR and thus demodulation accuracy in the combined signal.

2. SIGNAL MODEL

In this paper, we address a moving vehicle transmitting a telemetry waveform received at spatially diverse receive sites. Telemetry waveforms, as specified in the IRIG Telemetry Standard [5], can be represented as continuous phase modulated (CPM) waveforms,

$$x_T\,(t) = e^{j(2\pi f_0 t + \phi(t))}, \tag{1}$$

where the information is fully contained in the phase, $\phi(t)$ of the transmitted waveform, $x_T(t)$ The spatial diversity combining application is illustrated in Figure 1.

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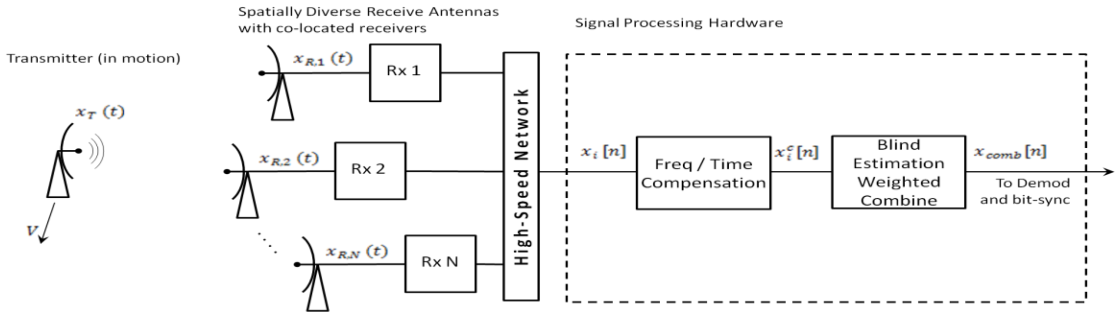

Figure 1 - Multiple antenna combining example, the output of this processing chain is the input to demodulation and bit-sync

Each antenna receives a signal that has passed through a unique radio channel. Models of wireless propagation channels can be extremely complex and consist of time-varying path and fading losses, delay spread and Doppler spread. These effects are caused by path loss, transmit and receive antenna patterns, multi-path interference, and other various atmospheric effects which vary based on application.

To model these effects to high fidelity, it is common to use a multi-ray scattering model with a convolutive impulse response (typically modeled as a FIR filter) [6]. In this work, we assume that the inverse bandwidth of the transmitted signal is much greater than the delay spread of the channel. This is common in situations where the line of sight ray dominates the received signal and the transmitted signal is narrowband. Thus, the channel effect can be modeled as a multiplication by single complex weighting with a time delay

Thus, if we have M receive antennas, the received signal at antenna *i* is,

$$x_{R,i}(t) = \alpha_i(t)e^{2\pi f_o\left(t-\tau_i(t)\right)+\phi(t-\tau_i(t)}, \qquad (2)$$

where α_i represents the complex weighting applied by the channel and $\tau_i(t)$ represents the delay due to the range between the transmitter and receiver. A digital receive chain might include an analog down conversion (ADC) and filtering, then an analog to digital converter at a desired sample rate, finally followed by a digital down conversion and filtering. This results in a set of complex baseband I and Q samples which can be represented as,

$$x_{\,i}\,[n] = \alpha_i(nT)e^{j(\phi(nT-\tau(nT)))}\;e^{j2\pi f_i(nT)} +\;\eta(nT), \qquad (3)$$

where T is the sample period of the ADC, f_i is a time varying frequency offset which incorporates Doppler shifts and clock mismatch between transmitter and receiver, and η is independent additive white Gaussian noise. Note that this simplified formulation assumes ideal filtering during down conversion stages. The goal of the spatial diversity combiner is to estimate α_i, τ_i and f_i with the goal of coherently combining the *M* signals in such a way as to maximize SNR.

3. APPROACH

The spatial diversity combiner proceeds in two steps. First, the *N* signals must be modified so that they are time and frequency aligned. Then the signals are combined with weights computed using blind beamforming subspace methods.

3.1. Time and Frequency Compensation

To align the received signals in time and frequency it is necessary to choose a reference signal. If we assume *i* = 1 is the reference we can represent the complex baseband signals as,

$$x_i[n] = \alpha[n-\Delta_i]e^{j\emptyset[n-\Delta_i]}e^{j2\pi f_i nT} + \eta[n], \qquad (4)$$

where Δ_i and f_i and the sample and frequency offset respectively. Since only relative offsets are necessary we can set $\Delta_1 = 0$ and $f_1 = 0$. Thus, the goal of the time and frequency compensation is to determine the time varying Δ_i and f_i for *i* = 2….*M* such that $x[\eta]$ add coherently *i*. This can be accomplished by choosing parameters which maximize an inner product between the reference and each other signals compensated versions of the other signals.

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$$[\Delta_i, f_i] = \arg\max_{\Delta_i, f_i} x_1^H x_i^c, \tag{5}$$

where x_i^c is the vector of compensated samples given by

$$x_i^c[n] = x_i[n + \Delta_i] e^{-j2\pi f_i nT}, \text{ for } n = 1 \dots N. \tag{6}$$

The expression being maximized in Equation 5 is known as the complex ambiguity function. These values can be efficiently computed by implementing a low pass filter of the mixing product between the signals [7][8]. The computation and tracking of the time and frequency offsets are essentially the determination of the time difference of arrival (TDOA) and frequency difference of arrival (FDOA) between the receive signals.

The capability of these algorithms to perform frequency and time compensation is bounded by the ability to synchronize the local oscillators and sample rates of multiple receivers. Modern receivers with GPS synchronization should obtain accuracy +/-10 nanoseconds which should be sufficient for the majority of telemetry applications.

It is worth noting that a byproduct of this approach to multiple antenna combining could be the geolocation of the transmitter based on standard TDOA and/or FDOA processing. Of course, this capability will depend on the geometry of the receive antennas as well as the accuracy of time and frequency calculations. Nevertheless, providing an additional data point for the physical location of an object transmitting telemetry could be of great use to the test community [9].

3.2. Weighted Combine

Once the frequency and time compensation is complete the combined signal can be created using a weighted sum of compensated received signals. In the following we detail the method of blind beamforming using a subspace approach, similar to that described in [3]. We can collect a set of N samples in a matrix formulation as follows,

$$X_c = [x_1^c \dots . x_N^c], \tag{7}$$

where the columns of X_c are the compensated sample vectors from the spatially diverse receive antennas. The columns of X_c are assumed to be noise matched, i.e. the noise is at the same level for each signal. A suboptimal, but heuristically good approach to determine combiner weights is based on the basis for the columnspace of X_c. These weights can be computed using the singular value decomposition (SVD).

$$X_c = U \Sigma V^H \tag{8}$$

For our problem of a single transmitted signal with multiple received signals we can show that the combining weights can be directly extracted from the first column of V. More explicitly,

$$x_{comb} = \sum_{i=1}^{N} V_{i,1}\, x_i, \tag{9}$$

where $V_{i,1}$ is the i^{th} element of the first column of V.

4. RTS TELEMETRY MODERNIZATION

The Reagan Test Site (RTS), located at the Kwajalein Atoll in the central Pacific has tracking telemetry sites located on two islands separated by approximately 80 km. During a typical tracking mission, antennas on each island are used to co- track a particular object for weather and multi-path diversity. MIT Lincoln Laboratory has developed a software defined radio based architecture for the Reagan Test Site Telemetry Modernization (RTM) program, which will enhance the current operations of the ground based telemetry systems and enable new modes of operation [10].

At each antenna facility commercial off the shelf (COTS) Receiver modules are used to perform the RF down conversion, wide band tuning, digitization, narrow band channelization and filtering functions. Each narrow band link is then sent to the central Telemetry Processing center on Kwajalein over a high speed fiber network where software defined radio processing techniques are used to perform telemetry signal processing. Software modules, running on general-purpose computers perform signal and data processing that have been traditionally performed in special purpose hardware based components. This provides the flexibility to scale and adapt to future needs, such as spectrum change, increased need for capacity, and changes to modulation, encoding, and compression.

The combination of wide baseline telemetry receive sites, high speed fiber network, and the increased capabilities of the RTM program make RTS an ideal location to validate and test spatial diversity combining techniques. Currently the RTM program has installed a single prototype receiver and software defined radio server and will install an additional prototype system on a different island and make GPS synchronized multi-site data collections. This will allow us to fully characterize the performance of the combining algorithm specified here versus traditional analog and digital combining approaches.

5. SUMMARY

We have proposed to apply blind channel estimation and beamforming techniques to create a spatial diversity combiner for telemetry applications. This approach will be validated and its performance characterized as a part of the RTM program.

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