INVERSE BEAMFORMING FOR NAVIGATING IN MULTIPATH ENVIRONMENTS

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ABSTRACT

Radionavigation in indoor and urban environments suffers from the effects of severe multipath and low signal strength. In this paper, we present a new technique, Inverse Beamforming, designed to reduce multipath power using signals from purpose deployed beacons. This technique complements other multipath mitigation methods which receivers use to make pseudorange measurements. Inverse beamforming is based on array signal processing by the user; however, a user needs only a single antenna, and the array itself is housed by the beacon (hence the name). Thus, a mobile user is not required to carry a cumbersome antenna array while taking full advantage of array signal processing gains. We present the concept and results of a laboratory test for this technique.

Index Terms **-** Navigation, Array signal processing, Multipath channels, Land mobile radio propagation factors

INTRODUCTION

GPS-based geolocation and navigation are critical functions for both military and commercial systems, yet GPS has several well-known limitations. First, the weak GPS signal is difficult, if not impossible, to accurately track indoors and in urban canyons; second, the GPS signal can be jammed; and third, multipath corrupts GPS positioning accuracy. The Defense Advanced Research Projects Agency (DARPA) is investigating solutions to these limitations with the Robust Surface Navigation (RSN) program.   RSN's approach to navigation is twofold: use Signals of Opportunity (SoOP) to navigate in environments where GPS navigation is unavailable, and develop new techniques to mitigate the effects of multipath. Combined, these two approaches are expected to produce a reliable and accurate means of user navigation in challenging environments.

A SoOP is defined as any radio frequency (RF) emission not originally intended for navigation purposes, such as AM/FM/digital radio, TV broadcasts, cellular telephone networks, satellite communications, and so on. SoOP signals span a large range of frequencies and power levels, and multiple SoOP signals are typically available to a user even when GPS is not. The SoOP-based navigation technology being developed on RSN counters localized jamming or failure of GPS, and complements GPS in situations for which it was not intended. In addition to SoOPs, RSN scenarios may include purpose-deployed RF beacons as an auxiliary or primary signal source.

Multipath is a non-line of sight (NLOS) path that a RF signal may take between a transmitter and receiver. Figure 1 shows an example of multipath from reflections/diffraction off of metal studs within a drywall. A typical GPS receiver uses two or more correlators to estimate the correlation between the incoming signal and a reference waveform. Since multipath signals combine with the line of sight (LOS) signal, the estimated correlation includes a contribution from multipath components. If the multipath delay is on the order of the inverse bandwidth of the signal (chip duration for GPS) or larger, it can be eliminated using techniques such as narrow correlators [1], strobe correlators [2], or the Multipath Estimating Delay Lock Loop (MEDLL) from Novatel [3]. For example, multipath-induced error in a narrow or a strobe correlator is (in a first approximation) proportional to multipath amplitude.   The MEDLL receiver solves for individual path components, but extracting LOS from the combined signal is possible only if multipath is not too strong.

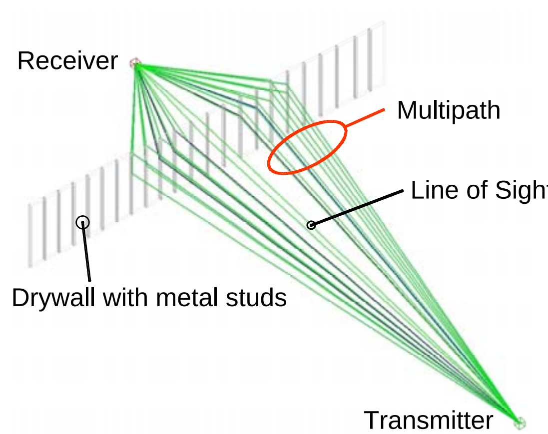

Figure 1: Multipath caused by metal studs within a drywall

For a dynamic user, multipath may be mitigated by averaging pseudorange measurements [e..g., see 4]. A typical receiver tracks the composite signal (LOS and multipath components are bundled), and the multipath component will “average out” if it is weaker than the LOS.

Another common way of mitigating multipath is using a specialized antenna, which suppresses gain from certain (typically low) elevation angles [5].

Unfortunately, applicability of all these methods is limited for a mobile user in urban environment. In this case, multipath delays can vary from a fraction of a meter to hundreds of meters. They almost invariably include small delay multipath where the delay is well within the inverse bandwidth of the signal. Moreover, multipath signals may have stronger power levels than the LOS signal. This latter case is poorly handled by specialized receiver correlators and by pseudorange averaging. Multipath arrival directions are not concentrated at low elevation angles, and thus are not mitigated by special antennas. RSN must deal with these challenges to achieve its goals.

Our approach for multipath mitigation includes several new techniques, which work together with previously known techniques to produce accurate LOS measurements. In this paper, we present one of the RSN algorithms under development, Inverse Beamforming, which is designed to mitigate the effects of multipath using purpose-deployed beacons.

INVERSE BEAMFORMING DESCRIPTION

Common array signal processing techniques (beamforming algorithms) can reduce the power level of the multipath signal components by exploiting the angular diversity of the signal propagation paths between the transmitter and receiver. However, a conventional application of beamforming encounters two difficulties. If the receiver is to perform beamforming, the user must carry an antenna array. This may be feasible for a vehicle, but becomes cumbersome for an individual on foot. For beamforming by the transmitter, the beacon must know the location of the user, and it is not clear how one beacon may serve multiple users with the same signal. Our Inverse Beamforming technique combines the advantages of beamforming both at the user and at the beacon, but without their drawbacks; the beam is formed by an antenna array at the beacon, but the individual users do the array signal processing.

Inverse Beamforming requires that the beacon has an antenna array with each element transmitting spread spectrum signals at the same frequency and controlled phase, but with different codes. The user knows the orientation of the beacon antenna array, its location, and codes. It is also assumed that the user has an approximate estimate of its position, thus being able to estimate the LOS direction to the beacon (this latter assumption is common for navigation applications). Whereas the beacon is required to have an antenna array, the user is only required to have a single omnidirectional antenna and enough channels to separately track the different codes from the beacon.

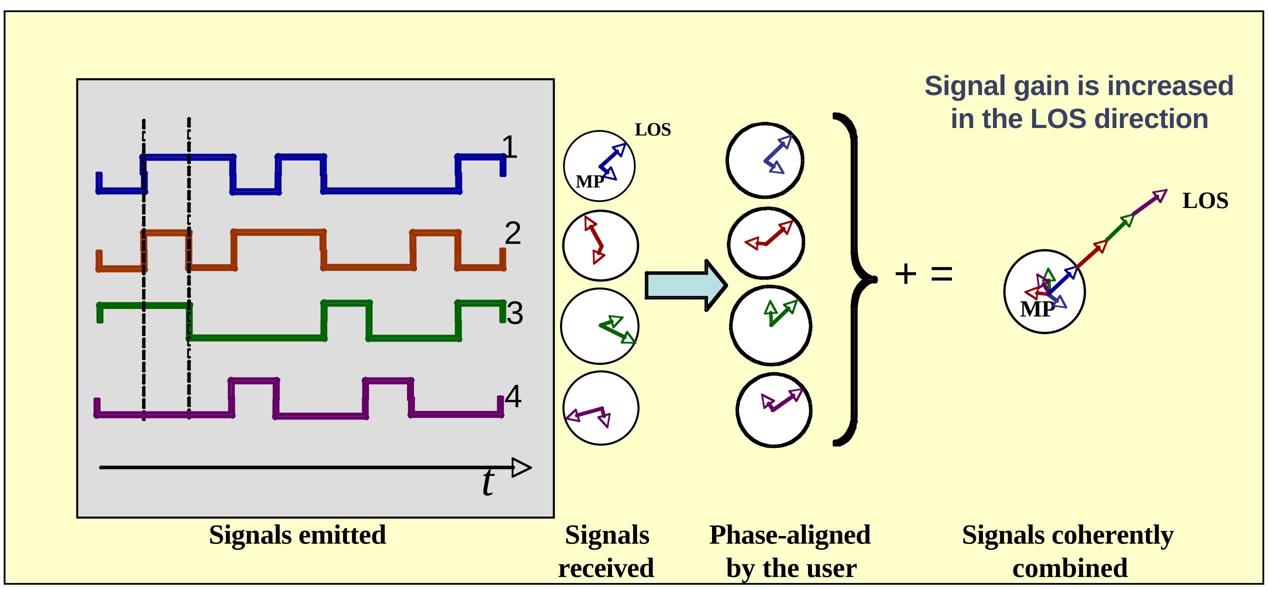

Figure 2: Inverse Beamforming Phaser Diagram

Inverse Beamforming takes advantage of the fact that the signal phase for each beacon code (channel) at the user will differ due to the different propagation delay between each beacon antenna element and the user antenna. If the beacon array orientation and approximate LOS direction is known, then the phase difference for the LOS component can be readily estimated. However, the same is not true for a multipath component, as it travels along some different and unknown path.

The user receiver de-spreads (correlates) each channel at the desired correlator delay and estimates the signal phase (i.e. the I and Q components) for each channel. The signals from each beacon antenna array element are then coherently combined in the LOS assumption. This is done by simply rotating the complex phase for each channel by an amount computed from the beacon orientation and geometry in the LOS direction. The LOS component will then be constructively amplified, and in contrast, any multipath component will be amplified less or even attenuated.

This concept is illustrated in Figure 2. In this example, there are 4 antenna elements, each transmitting a different BPSK code. Received signals are illustrated by phasers, which are separated into a LOS and multipath component for the purposes of this discussion (of course, they are combined in the real world). The user aligns the phases of LOS components using knowledge of the geometry and combines all four signals. The LOS component is amplified whereas the multipath component is not.

One can see that this technique accomplishes several goals: one beacon can serve multiple users; a beacon does not have to know the positions of users (no datalink from the user to the beacon is necessary); a user can have a compact omnidirectional antenna; and yet the full benefits of beamforming can be realized by the user.

INVERSE BEAMFORMING EXPERIMENT

Inverse Beamforming was evaluated using data collected in the controlled environment of an anechoic chamber. The test setup shown in Figure 3 introduced a 28 ns multipath delay relative to the LOS signal delay. The LOS was also attenuated with foam material so that the LOS signal strength was not significantly larger than that of the NLOS. The beacon antenna array was a four-element linear array with 0.75λ element spacing. The beacon signals were centered at a frequency of 2.45 GHz and were BPSK modulated at 80 mega-symbols per second (Msps). The four codes were each 2^{15} symbols long, and were generated by thresholding Matlab-generated noise sequences to ensure good inter-code orthogonality. Post-test, the channel impulse response was computed by applying a Weiner filter to the correlation measurements collected from the receiver. This separates

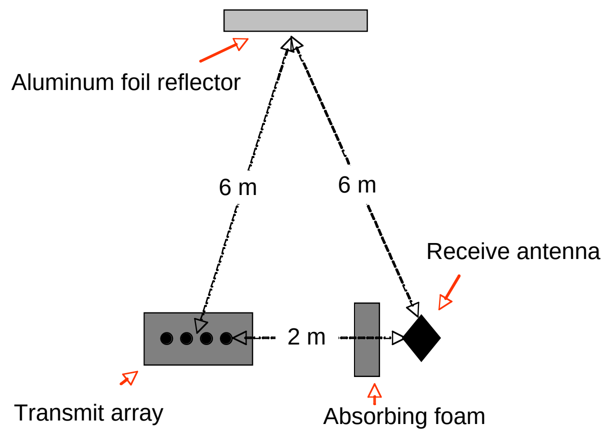

Figure 3: Inverse Beamforming Test Configuration

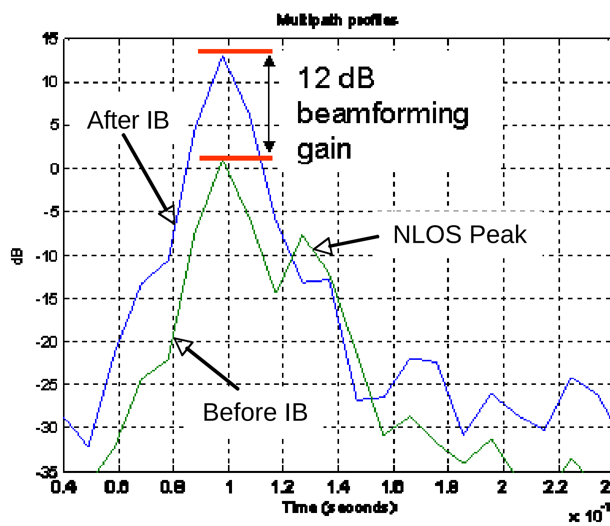

Figure 4: Inverse Beamforming Results

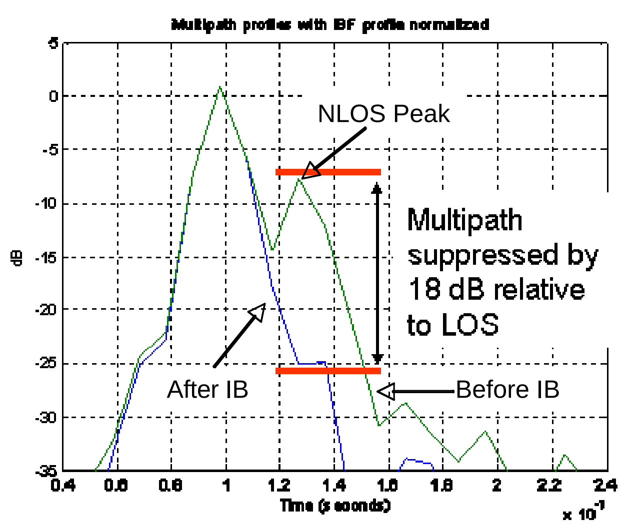

Figure 5: Normalized Results

the multipath component in the time domain and clearly shows the effect of the Inverse Beamforming.

Figure 4 shows the transmitted signal before and after applying Inverse Beamforming (the former being the average amplitude of all 4 signals). As shown, the LOS signal amplitude increased by 12 dB. Figure 5 shows the normalized signals before and after beamforming to highlight the suppression of the multipath signal by 18 dB. These results are consistent with the theoretical pattern for a four-element linear array with 0.75λ element spacing (at least 12 dB discrimination for aspect angles between 45 and 90 degrees; angle to reflection path was ~80° for this test).

CONCLUSIONS

The Inverse Beamforming algorithm has been shown to mitigate multipath components based on the angular diversity of their paths. The key innovations of Inverse Beamforming is that 1) it enables users to have the benefits of array signal processing with only a single-element compact antenna, and 2) a single phased-array beacon enables multiple users to simultaneously beamform to it.

Inverse Beamforming mitigates all multipath components regardless of their delay, including small delay multipath, by reducing the multipath power. Even though multipath may not be fully eliminated, any power reduction is beneficial. Inverse Beamforming can be used as a first line of defense against multipath, and any technique for producing pseudorange measurements that suffers from multipath effects will benefit from a reduction in multipath power. Other RSN pseudorange estimation techniques, while beyond the scope of this paper, also benefit from a reduction in multipath power.

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