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Reduced complexity crosscorrelation interference mitigation in GPS-enabled collaborative ad-hoc wireless networks – Theory ☆

Catalin Lacatus *, David Akopian, Mehdi Shadaram

Department of Electrical and Computer Engineering, University of Texas at San Antonio, United States

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ABSTRACT

Localization based services rely on Global Positioning System (GPS) receivers embedded in the network nodes, but the satellite signal availability is often limited in indoors environment. Collaborative network-assisted GPS algorithms addressed this issue by communicating various assistance data between the nodes or transforming open-sky nodes into virtual GPS satellite transmitters (pseudolites). Even though such approach improves the coverage, the crosscorrelation problem surfaces due to masking of relatively weak available satellite signals by stronger pseudolites. This paper proposes reduced complexity algorithms to mitigate such a self-jamming (near/far) effect in ad hoc networks. The idea is based on adaptive modifications of dispreading GPS codes in receiver nodes to minimize interference caused by strong pseudolite signals. An optimization problem is formulated for the minimization of interference using mean squared error (MSE) as a cost function. Then computational optimization is achieved through adaptive implementation and parameterized dimension reduction of the optimization problem.

1. Introduction

Node localization in ad-hoc and sensor networks is important for many applications such as optimization of data routing algorithms, mapping of sensed data, tracking of nodes, etc. [1–3]. Many of these applications use nodes with embedded Global Positioning System (GPS) receivers for user position estimation [4–10]. GPS is designed for open-sky applications and its coverage is often limited in many indoors and urban canyon areas. Recently proposed collaborative network-assisted GPS algorithms addressed this issue by communicating various assistance data between the nodes [11] or even transforming open-sky nodes into virtual GPS satellite transmitters (pseudolites) to assist the others [12,13]. Even though such approach improves the coverage, a multiple access interference (MAI) or otherwise crosscorrelation problem occurs, as strong signal pseudolites mask other satellite signals due to near/far phenomena. The pseudolites were initially proposed to complement the satellite constellation for testing GPS receivers, and then used for indoor positioning and automatic landing [14]. Different configurations of augmented GPS systems and their benefits are described in [15] for urban canyon and indoor environments. Direct ranging, mobile, digital datalink pseudolites and synchrolites are some of pseudolite types, and in this paper, nodes contain direct ranging pseudolites that transmit GPS-like signals. Also, in military applications, the crosscorrelation effects can originate from jamming signals.

One should understand the operation of the GPS receiver to formulate the problem. GPS receivers synchronize to satellite signals and estimate user-to-satellite ranges. Then trilateration methods are used for position computation [7,8]. Advanced receivers for weak signals exploit wireless assistance from other sensors or beacons, long integrations and massive

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* Corresponding author.
E-mail address: catalin.lacatus@utsa.edu (C. Lacatus).

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correlations [16–20]. Even though a progress has been recorded in this area still indoor and urban environments are very challenging for the receivers because of weak signal strengths, severe multi-path, colored noise, crosscorrelation effects, etc.

The GPS receiver typically synchronizes to satellites or pseudolites in two steps called acquisition and tracking. Once the signal has been acquired, the receiver switches to tracking mode. For conventional and advanced acquisition methods the readers are referred [7,8,17,20]. This paper addresses the receiver operation during the tracking mode. In weak signal conditions when the strong pseudolite signals jam the week satellite signals, the tracking of satellite signals is often interrupted and the acquisition process has to be repeated again. It is inconvenient as the acquisition process is very time and resource consuming. In indoor environments, the received signal powers of satellite and pseudolites may differ by more than 35 dB because of diverse propagation channels. GPS signals were initially designed with cross-correlation interference immunity of about 20 dB which is apparently not sufficient for ad-hoc networking in weak signals.

The synchronization is performed by correlating received signals with locally generated replica of the expected satellite codes as GPS is a spread spectrum system. Received signal is composed of multiple satellite codes emitted by the transmitter and contaminated by channel distortions. Conventional approaches use the same codes in receivers and transmitters (satellite or pseudolite) and, as it is mentioned above, this does not provide sufficient immunity against crosscorrelation effects. Some advanced solutions modify local (dispreading) codes in the receivers in order to reduce these effects. For dispreading code optimizations, one can use linear or non-linear approaches. The traditional non-linear interference cancellation techniques cannot be applied to GPS receivers because of a lack of training sequences, high computational loads and time delays. However, the linear receiver techniques are feasible. As such, decorrelator and MMSE detectors [21] are typically used for mitigating the MAI effects in spread spectrum systems. But the MMSE approach is computationally intensive due to required autocorrelation matrix inversions. To simplify the processing, some investigators estimate the cross-correlation signal and subtract it from the weak signal channel [22–24]. This solution is not optimal and computation overhead is still high especially in the presence of strong satellite signals. A more computational efficient method [25] employed the partitioned subspace projection method to mitigate the self-interference during acquisition stage. An ad-hoc solution is suggested in [26] using an additional orthogonalization process for better separation of weak and strong channels. There, the authors observed that the performance of their method deteriorates with a few stronger signals and the method fails when there are more than four strong signals. Another idea of successive interference cancellation was introduced to solve the pseudolite near-far problem in [27], while the feasibility of the parallel interference cancellation technique was investigated in [28]. In order to mitigate the interference the literature presents different adaptive optimization approaches based on linear and nonlinear programming as well as evolutionary algorithms such as genetic algorithm. The main drawback of the genetic algorithm methods is in a typical convergence to sub-optimal solutions. Also, the adaptation of the fitness function to the changing interference pattern in the operational environment requires a high computational complexity and high latency.

In this paper, we propose novel optimized dispreading code design approaches to minimize cross-correlation effects in GPS-enabled ad-hoc/sensor networks. Different from the known techniques, optimal solutions are found with scalable computational constraints that trade-off the reception performance versus complexity. The algorithms adapt to the type of interference with the code tracking and code updates performed in parallel. The optimization based on proposed gradient approach provides the convergence and the optimality of the linear problem. In our approach, the stochastic interference behavior is modeled through the received correlation matrix, which is computed using samples accumulated over a specified time period. Further, the gradient of the cost function will drive the dispreading code toward the optimal value.

The algorithms are implemented to minimize the mean squared error (MSE) during signal tracking process. Our methods are based on the convex optimization theory where the MSE is regarded as a convex function in the dispreading code. At the optimal point (optimal dispreading code), the algorithm maximizes the signal-to-interference-plus-noise ratio (SINR) for the weak satellite signal. The compact form of the MSE gradient makes this method easy to implement in an adaptive and computationally efficient way (in a code-adjustment loop). Our first method adaptively finds the optimal MMSE solution without matrix inversion. It has a computation complexity of order $O(N^2)$ versus $O(N^3)$ operations as in the conventional MMSE approach based on matrix inversion. Examples of additional complexity reductions through thresholding and quantization of the autocorrelation matrix are provided. The proposed approach is feasible for channels being jammed by the strong signals [29]. Next, we propose a scalable MMSE method, called group-weighting, with parameterized complexity constraints. It has $O(M^2)$ operations, where parameter M provides the trade-off between the interference cancellation performance and computational load. The group-weighting method is equivalent with the conventional MMSE solution when $M = N$. The proposed algorithms will provide optimal solutions for all types of interference.

The paper is organized as follows: we provide the system model in Section 2, followed by the problem formulation in Section 3. Section 4 describes the proposed adaptive algorithm. Section 5 presents parameterized reduced complexity methods. Performance analysis, numerical and simulation examples are discussed in Section 6. Finally, we present concluding remarks in Section 7.

2. The collaborative ad-hoc wireless networks model

From the node localization point of view the GPS-enabled collaborative ad-hoc wireless network components are nodes with embedded GPS receivers and transmitters (embedded pseudolites) and possibly stationary pseudolites driven by