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Innovative Signal Processing Solutions for Next-Generation Satellite Navigation Systems

By

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Abstract

From the development of the first satellite navigation system during the late 1950s, we have been observing a continuous modernization process. Global Navigation Satellite Systems (GNSSs) are nowadays the most widespread technology for positioning, navigation and timing (PNT) and have been traditionally deployed exploiting medium earth orbit (MEO). Although characterized by a stronger Doppler effect, PNT based on low earth orbit (LEO) constellations has been investigated as a radical system change or as an enhancement for existing GNSSs, to provide better position, velocity, and time (PVT) estimation accuracy, signal robustness, and service availability.

As constellations are growing, providing a reliable service becomes more difficult. Indeed, timely information about orbit determination and system time needs to be provisioned to each satellite by a network of ground stations. However, continuous radio visibility cannot be ensured for large constellations, such as LEO fleets; therefore, to foster space segment autonomy, the use of inter-satellite links (ISLs) has been foreseen in the last years as a natural system enhancement to grant a decentralized access to information. Moreover, the adoption of optical inter-satellite links (OISLs) has been proposed to achieve improved clock synchronization, precise ranging, and high data rate communications, resulting in an overall better accuracy and autonomy. However, given the limited number of simultaneous ISLs, the dual optimization of data and navigation performance metrics requires a careful assignment of connections to the available transponders.

PNT services are available thanks to the simultaneous broadcasting of multiple signals and signal design innovation has been often steered toward powerful multiplexing schemes, to combine multiple signals into a single composite transmitted signal. Indeed, modern signal multiplexing methods allow to seamlessly enhance the existing signal-in-space with newer signals and to support frequent and rapid reconfigurations of the transmitted signal set, promptly adapting to system upgrades

and future needs. However, as the number of signals grows, efficient multiplexing becomes more challenging, resulting in significant power loss.

Nevertheless, GNSS receivers are also continuously evolving as a primary answer to user demands. Advanced algorithms and new processing strategies are therefore exploited to improve PVT estimation performance, leveraging, for instance, multiple signals or modern receivers' connectivity (e.g. smartphones), but their applicability in new GNSS scenarios should be assessed.

The aim of this dissertation is to explore innovative prospects for future satellite navigation systems, proposing and analyzing several solutions at system, signals, and user level. The objective of this work has been therefore to seek for performance improvements, acting at various levels of the GNSS value chain, yet fulfilling possible upcoming needs and constraints. In this context, this work focuses on improving the use of resources, both upstream, to enhance signals and services, and downstream, by leveraging such signals for a better user performance. Specific research questions were addressed for this purpose: *how can ISLs be assigned while optimizing data and navigation performance? Can multiple signals transmission be more efficient? How can we leverage signal multiplicity and receiver technologies to improve accuracy and robustness of the final PVT estimation?*

The first part is dedicated to the space segment evolution. The problem of optimizing the contact plan for a GNSS equipped with OISLs is specifically addressed and optimal range-based satellite positioning is achieved through the dedicated design of objective functions and satellite network modeling. A contact plan design scheme is presented, based on a degree constrained minimum spanning tree (DCMST) heuristic. Results on the Kepler system, a novel GNSS proposal, show that a Position Dilution of Precision (PDOP) improvement of 85 % is reached on average by the optimized contact plan with respect to a generic scheduler that disregards the geometrical distribution of the chosen links.

The second part is focused on multiplexing methods for future satellite navigation systems. An input optimization method for multicarrier multiplexing algorithms is presented, to improve the use of power resources in upcoming payloads. A bad choice of input configuration can, in fact, severely affect the multiplexing performance causing a power loss of more than 20%. Avoiding such poorly performing configurations motivates the proposed algorithm.

The third part is dedicated to user technologies and signal processing algorithms, focusing on those techniques that especially fit upcoming changes. The contribution of this dissertation to user-level advancements is therefore twofold: (*i*) the definition and testing of a processing architecture, enabled by the higher complexity of modern receivers, that leverages multiple signals to provide improved accuracy; (*ii*) the proposal of a crowdsourcing algorithm, enabled by the enhanced connectivity that characterizes the current and upcoming user base, with the goal to hinder intentional interference threats.

A generalized theory of the concept of meta-signal, extended to orthogonal signals, is thus proposed, to address (*i*) and efficiently exploit band-limited signals while improving Doppler robustness. The method has been compared to a typical meta-signal implementation and its robustness has been tested against different impairments and scenario settings for next-generation GNSSs. This approach grants accurate signal tracking with an adjustable estimation accuracy. Such predominant flexibility, together with the Doppler robustness, make the investigated architecture suitable to rapidly adapt to the fast-changing needs of future and alternative GNSSs.

Enhanced connectivity was explored for collaborative approaches against jamming (*ii*), a serious threat for current and future GNSSs due to received signals' low power. Congested areas are particularly sensitive to these kinds of attacks, but they also present an opportunity to leverage crowdsourced data for threat localization. In this framework, a jammer localization scheme based on a physics-based learning approach is proposed. The interference localization method is based on a signal propagation model, enhanced through the use of physics-based path loss modeling and an augmented, data-driven, component. This method proved to seamlessly adapt to very different propagation scenarios, without any prior information about the characteristics of the jammer.