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A New Peer-to-Peer Aided Acquisition Approach Exploiting C/N_0 Aiding

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***Abstract*—The aim of this paper is to present an acquisition strategy for Global Navigation Satellite System (GNSS) signals exploiting aiding information provided by GNSS receivers in a Peer-to-Peer (P2P) positioning system. This work sheds light on the benefits of sharing information regarding the received satellite signal power: the Carrier-to-Noise density ratio (C/N_0) estimated by aiding peers relatively close to each other, is used to optimize signal acquisition capability in terms of detection performance as well as Mean Acquisition Time (MAT). The proposed approach has been validated and assessed using real data collected with an experimental setup in light indoor conditions and by means of simulations. The performance obtained has also been compared with an Assisted-GNSS (A-GNSS) like acquisition strategy, showing the benefits of the availability of C/N_0 aiding information in terms of MAT.**

Keywords: Peer-to-peer, C/N_0 estimation, Galileo, Assisted-GNSS, Aided Acquisition.

I. Introduction

The paradigm of a Global Navigation Satellite System (GNSS) Peer-to-Peer (P2P) cooperative localization consists in the use of direct inexpensive communication links among nodes (peers) of a network equipped with GNSS receivers [2]. The communication channel is mainly used to transmit GNSS collaboration data generated by either open sky (OS) GNSS users or light indoor (LI) peers to improve the localization performance of a potential LI user demanding help to get a position fix. LI users can be identified as receivers having an antenna which captures the Signal In Space (SIS) with a moderately low C/N_0, i.e. less than 40 dB-Hz, typically obtained in urban canyons, forest canopies and indoors [3].

A scenario characterized by a cluster of peers, composed by one or more OS peers and several LI peers (e.g. close to a window in static conditions) spatially spread in a limited range (e.g. less than 1 km, in order to ensure the validity of P2P aidings) has been adopted in our study and will be further explained in the following. Some peers, also called "aiding peers", are able to transmit GNSS aiding data to a LI peer requesting collaboration to get a position fix. It is interesting to note that the latter peer in turn, after a successful aided acquisition and Position Velocity and Time (PVT) solution, will consequently be categorized as an aiding peer, able to transmit and share its GNSS data with other peers in difficulty. It is worth mentioning that in this work, aiding techniques based solely on the exchange of satellite information (GNSS data only) are considered and thus the focus is on the physical layer of a GNSS receiver. This approach, known as aided signal acquisition, is characterized by processing useful data shared by peers "nearby" which mainly estimate generic GNSS data like Doppler frequency, code delay, and Carrier-to-Noise density ratio (C/N_0) corresponding to each satellite in view, as will be discussed in the following. In this sense, the P2P concept is somehow similar to the Assisted-GPS (A-GPS) approach in that it improves on standard GPS performance by providing information, through an alternative communication channel, that the receiver would ordinarily receive from the satellites themselves [4]. One disparity though, is the achievable time synchronization between peers or nodes, particularly when it comes from asynchronous networks. In fact, asynchronous networks like Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS) and Wideband Code Division Multiple Access (WCDMA) networks offer a time synchronization of about 2-3 seconds at the Mobile Station (MS) unlike synchronous Code Division Multiple Access (CDMA) networks which provide a time accuracy typically of the order of μs [4]. This is also the accuracy offered by most algorithms used in Wireless Sensor Networks (WSN), valid for the P2P concept [2]. However, asynchronous networks will be taken into consideration in the following, as CDMA networks are mainly deployed in America and eastern Europe and are almost non-existent in the rest of Europe, except some Nordic countries.

The first important information the aiding peers can easily provide to an "aided" peer is an estimate of the Doppler frequency shift for each satellite in view. In fact, a rough knowledge of the Doppler frequency results in a dramatic complexity reduction, by decreasing the size of the search space which is computed by the aided peer. The

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Cross-Ambiguity Function (CAF) is then computed only on a reduced number of frequency bins around the expected value, which speeds up acquisition and reduces the Mean Acquisition Time (MAT). In addition, the estimated Doppler aiding data can also be used to compensate the Doppler effect on the code, modifying the local code rate to properly generate the local code samples in the acquisition process, thus enabling long coherent integration time (T_{int}). Moreover, the frequency range of the Doppler search can be selected by the aided peer considering the total uncertainty on the aiding information, mainly due to the quality of the local oscillator on-board different peers but also to the quality of the Doppler estimation process. An important requirement, in order to properly exploit Doppler aiding information, is to have frequency synchronization between the local oscillators included in the peers' front-ends (compensating eventual clock frequency offsets and drifts).

Another significant aiding parameter is the estimate of the code delay information which has already been discussed in [2], where a novel aided acquisition strategy, suitable for Galileo E1 mass-market receivers, has been presented focusing on the advantage of having aiding information on the secondary code delay of the Galileo E1 pilot channel. In fact, provided with a somehow reliable secondary code delay estimate, the acquisition engine first wipes off the secondary code from the received signal, and then computes the CAF on a single or several primary code periods, much shorter than the secondary code period. This strategy obviously has a considerable impact on complexity reduction as it limits computations by a significant factor and simplifies the local code generation. The effect of secondary code delay aiding errors is also analyzed, and numeric synchronization requirements are derived confirming that the P2P alternative is a sound and feasible approach. In fact, the P2P paradigm coupled with a good synchronization infrastructure is expected to provide considerable benefits over the A-GNSS approach, where the sharing of secondary code delay information is not even foreseen: A-GNSS standards [5] only mention generic code delay assistance, without mentioning secondary code delay in case of Galileo.

The third aiding parameter is the C/N_0 aiding which will be the central topic of the paper hereafter. Although A-GNSS standards mention it as an assistance parameter [5], the C/N_0 assistance procedure is not clearly defined, i.e. how the parameter is used to save up computations and reduce the time to first fix. The benefits of sharing C/N_0 data in a P2P aided acquisition strategy, have been highlighted in this paper. Combining C/N_0 aiding data from multiple peers, the aided peer can determine with good confidence the satellites in view and set up the acquisition engine appropriately. For a low estimated C/N_0, it is possible to increase the integration time, choosing an adequate number of coherent and non-coherent integrations, thus improving the acquisition performance. For an A-GNSS approach, this concept is not so sound by definition, because the environment at the assisting base station (different interference conditions and excellent position for signal reception) is very different from the one at the user site where the received signal is most likely attenuated and contaminated from multipath and possible interference.

The next Section is devoted to describe the idea behind the P2P C/N_0 aiding approach. In detail, an analytical expression is derived in order to properly set up the integration time according to the C/N_0 estimates provided by aiding peers. In addition, C/N_0 estimation issues are also briefly discussed. In Section III, an experimental P2P setup which is used to test the proposed approaches, has been thouroughly described and the resulting performance has been evaluated. The proposed approach has also been validated and assessed using real data collected with an experimental setup in light indoor conditions and by means of simulations. The next Section introduces possible weighting approaches useful for exploiting aiding info from multiple peers. Moreover, these approaches have been assessed by means of simulations, in terms of MAT. The obtained performance has also been compared with an A-GNSS like acquisition strategy, showing the benefits of the availability of C/N_0 aiding information in terms of MAT. Finally, some conclusions are drawn in the last Section.

II. P2P ACQUISITION EXPLOITING C/N_0 AIDING

The main aiding parameter tackled in this work is indeed the C/N_0 aiding parameter. The idea stems from the reasoning that nearby peers having the same measuring capabilities, are characterized by similar estimated values of their carrier-to-noise ratio with respect to time. Some sources of instability may come from measurement noise, slightly varying environment, etc. so it remains to adjust this reasoning according to scenarios, by doing an appropriate weighted average of the estimated C/N_0 coming from available peers. The weights can be defined taking into consideration the distance between peers (using terrestrial measurements coming from WSN), and/or a pre-defined knowledge of the quality of the peer position (variance of its C/N_0 estimation, as will be discussed in Section IV-A). A proper integration time is then derived using an analytical expression as will be shown next, in the hope to detect the signal from the first shot, hence saving considerable acquisition time by skipping the process of trial and error of various values for the integration time. As previously mentioned, although A-GNSS standards mention the C/N_0 as an assistance parameter, there is still no clearly defined process to make use of it beneficially. Moreover, the same satellites can be seen on both sites with a different signal power: the assisting base station might as well receive a very clean satellite signal whereas the user requesting assistance could be in a hostile environment which would require an integration time several times longer than the proposed one. In the following, the C/N_0 aiding strategy is deeply analyzed and several approaches are taken into account.

A. Integration time vs C/N_0

An analytical expression which sets up a proper coherent integration time, as a function of the desired level of a simple acquisition metric SNR_C (a signal-to-noise ratio defined on the CAF), the estimated C/N_0 and the non-coherent accumulations, has been derived and is presented hereafter. Knowing that the signal-to-noise ratio at the output of the correlators (SNR_{out}) in the acquisition engine is equal to N times the signal-to-noise ratio at the input of the correlators (SNR_{in}), where N is the number of points over which the correlations take place, and assuming that the signal power is constant passing through the correlators, it is correct to conclude that the noise power at the output of the in-phase and quadrature correlators is N times less than the noise power at the input of these correlators.

On the other hand, SNR_C defined in [2] as

$$\mathrm{SNR}_C = \frac{{A_p}^2}{E\{W^2[n]\}} \tag{1}$$

can be re-written as

$$\mathrm{SNR}_C = \frac{C}{2N_0B}\lfloor N \rfloor \tag{2}$$

where B is the bandwidth of the receiver front-end filter, considering only coherent integrations and assuming that the sum of the output of the correlators follows a Rayleigh distribution. In case of non-coherent accumulations, the correlator outputs sum follows a χ^2 distribution. The value of SNR_C can be obtained after some derivations and simplifications as:

$$\mathrm{SNR}_C = \frac{C \cdot L}{N_0B(2+(L-1)\frac{\pi}{2})}\lfloor N \rfloor \tag{3}$$

where L is the number of non-coherent accumulations. From (3), it is easy to obtain the number of points over which to integrate (or the coherent integration time T_{int}), given an expected C/N_0, the number of non-coherent accumulations L, the receiver bandwidth B and the acquisition metric SNR_C, that is

$$\lfloor N \rfloor \geq \frac{\mathrm{SNR}_C(2+(L-1)\frac{\pi}{2})B}{L\frac{C}{N_0}} \tag{4}$$

B. C/N_0 estimation issues

It must be noticed that in a mass market GNSS receiver, the C/N_0 is an estimated parameter which oscillates with time (depending on the proprietary C/N_0 estimation algorithm used in the receiver as well as on the satellite elevation). In addition, different receivers in the same scenario can estimate different values of C/N_0, depending on the quality of the receiver front-end (noise figure of the components). For instance, it is known that different commercial GPS receivers can measure discrepancies of the order of some dB-Hz on average, but higher differences can also be noticed in some unfavorable cases [6].

These effects, as well as the operative scenario (open sky or indoor), must be considered in order to effectively exploit the sharing of C/N_0 estimates between peers. Antennas, front-ends, cables or other possible hardware involved are all characterized by a noise figure and affect the C/N_0 estimate. It is then required to calibrate the C/N_0 estimates coming from different peers so that a common valid understanding of these estimates is reached to share this information appropriately. Possible solutions include an a-priori meticulous calibration of the peers' hardware, and an automatic evaluation and compensation of eventual discrepancies in C/N_0 estimates. For instance, if there are N P2P users, and M ($M << N$) users always report C/N_0's significantly different, even when at short distance to other peers, a flag could be raised that the C/N_0 values of those M users should not be used.

III. Experimental setup and results

In this Section, an experimental setup to make a GIOVE-A E1 signal data collection, using multiple front-ends is presented. GPS signals have also been simultaneously processed to characterize clock stability and accuracy as well as synchronize the datasets with respect to precise GPS time. The analysis herein, is based on a specific dual-mode GPS and Galileo front-end, the SiGe GN3S Sampler v2 Sparkfun GPS-08238 [7] which contains a highly-integrated GNSS radio front end [8]. All measures have been taken on this specific research device, co-developed by the GNSS Lab at the University of Colorado and SiGe©, able to downconvert and sample L1 GNSS signals and communicate with a computer using a USB port. Raw samples have been saved in binary file using N-GENE©, a fully software GNSS receiver developed by the NavSaS group [9].

In OS conditions, N-GENE© can easily acquire signals of all GPS and Galileo (currently GIOVE-A and B) satellites in view, go into tracking mode and provide a rapid and accurate Position Velocity Time (PVT) solution. In addition, N-GENE can provide real-time information on the GPS time, clock frequency offset, code delay, Doppler frequency as well as the C/N_0 estimated for each acquired satellite. More importantly, N-GENE solving the PVT problem, can provide an exact time reference that is the GPS time, and estimate in real-time the clock drift of the local oscillator in the GNSS front-end. N-GENE is also able to provide a log of the afore-mentioned aiding data at each instant on the GPS time scale and correspond it to a sample number for post-processing results.

A. P2P setup

In a real GNSS data experiment, where the benefits of a P2P positioning scenario are to be highlighted, the ability to synchronize several communicating nodes with each other is of paramount importance. The communication and the synchronization between these nodes usually takes place in real-time. However, in our experimental P2P positioning setup only a rough time synchronization (using NTP protocol) between N-GENE software receivers running on the PCs used in the data collection has been carried out in real-time. In our setup, the accurate synchronization (up to a few μs) task has been postponed to the post-processing stage in this preliminary exploration of the P2P aiding potential where synchronization needs are to be assessed.

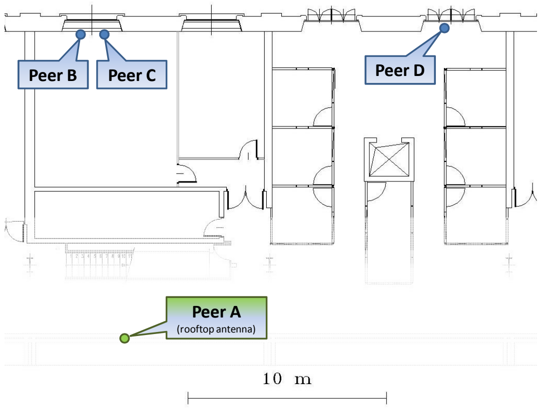


Figure 1. Scheme showing peers' position in the experimental P2P positioning setup.

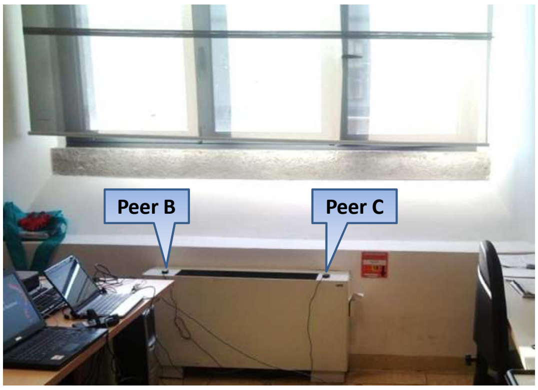


Figure 2. Peers B and C position in a P2P aiding static LI scenario.

Figure 3. Peer D position in a P2P aiding static LI scenario.

In our setup, each of these nodes consists of a personal computer (PC) i.e. desktop/notebook/netbook, a GNSS front end (FE) i.e. SiGe© GN3S sampler v2, and a patch antenna or a GNSS professional multi-frequency (L1/L2/L5) active antenna. The antenna is used to detect raw GNSS signals coming from satellites, the front-end is used to capture raw data to a binary file on the PC, after having sampled and translated the signal to intermediate frequency. The software receiver N-GENE© developed by the NavSaS group is the interface between data coming from the SiGe© front-end and the output binary data file on the PC.

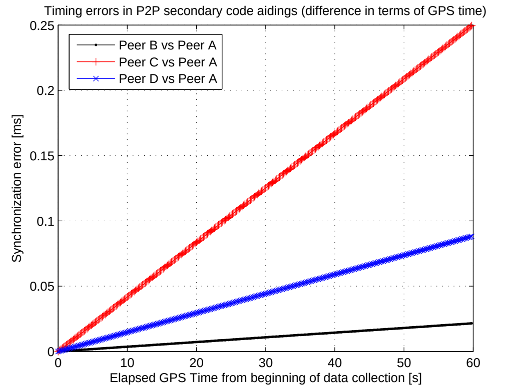
In this experiment, four nodes also called "peers" hereafter, were set up to capture both GPS and Galileo raw data from satellites with a relatively good elevation angle. For convenience, the four peers will be identified as peers A, B, C, and D thereafter and placed as shown in Fig. 1. Peer A is a bundle of a desktop computer connected to a FE connected to a GNSS professional multi-frequency antenna placed at the rooftop of our research building (static, OS). In other words peer A has an excellent view of the sky, is in a static position and qualified as OS user.

Similarly, peers B and C are a bundle of a PC, a FE and a commercial patch antenna placed just inside our navigation lab, close to the window (static, LI). While peer D is physically similar to the afore-mentioned peers B, and C (bundle of PC+FE+antenna), the data collection took place in the room next-door with the antenna positioned just in front of a window (static, LI). All peers in the experiment are static and a logging of synchronized data using the NTP protocol on all PCs, went on for 5 minutes. Peer C has been assumed to be the aided peer and peers A, B and D acted like aiding peers.

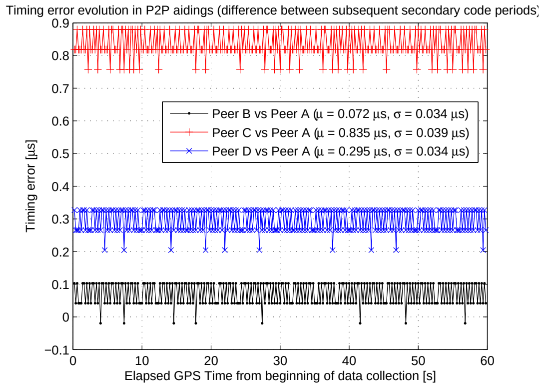
Peer A has been used to provide a synchronization reference as it is privileged (from other peers) by having a perfect open sky view (rooftop of building) and a professional antenna. It is also considered as an OS anchor peer.

B. Comparison of P2P aiding experimental results

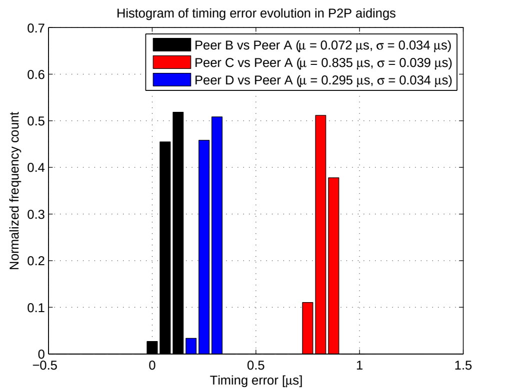
In the setup described above, experimental results due to algorithms exploiting the sharing of the three types of P2P aiding data, are presented. These results are to show the accuracy of the P2P aiding data (secondary code delay, Doppler and C/N_0 aidings), by considering the physical constraints introduced by time and frequency synchronization errors as well as C/N_0 calibration and estimation issues. Fig. 4(a) shows the time synchronization error, embedded in every secondary code delay aiding, between each LI peer (B, C, D) and the OS anchor peer A, assuming that all peers are perfectly synchronized at the origin of time. It is seen that, with no synchronization mechanism put in place, the synchronization error tends to grow linearly with a different slope for each peer, depending on the clock drift of each peer as will be shown in the following. The highest synchronization error is reached (after 60 seconds) by peer C with respect to peer A. However, looking at the difference of synchronization errors corresponding to subsequent secondary code periods (i.e. 200 ms for the GIOVE-A E1c pilot signal [10]), shown in Fig. 4(b), the time synchronization error is of the order of less than 1μs. This suggests that if a proper algorithm is put in place to synchronize the peers every 200 ms, the secondary code delay aiding can be very relevant as it reduces the analyzed code delay bins to just around one or two bins. Note that it is assumed that the cluster of peers is spatially spread in a



(a)



(b)



(c)

Figure 4. Comparison of time synchronization errors in P2P secondary code delay aidings (a), difference between subsequent secondary code periods (b), and corresponding histogram (c) with respect to the reference OS anchor peer A, over a data collection of 60 seconds, with no synchronization mechanism.

limited range $lessthan1$ km (i.e. a code delay discrepancy less than 3μs).

Fig. 5(a) compares the clock frequency offsets characterizing local oscillators at each peer's front-end. As can be seen, this considerably varies from peer to peer, but is in the range $-500 \div 1500$ Hz and relatively stable. Each peer then accounts for this frequency shift when estimating its pure Doppler frequency which is then shared with other peers. Fig.

Table I
EXPERIMENTAL RESULTS FOR P2P C/N_0 AIDING.

Peer ID	**Mean est.** C/N_0 [dB-Hz]	σ **of est.** C/N_0 [dB-Hz]	**Distance from aided peer (C)** [m]	**Mean** $\Delta C/N_0$ **w.r.t. peer C** [dB-Hz]
A *(OS)*	45.37	1.30	30	11.29
B *(LI)*	32.12	1.45	1	-1.96
C *(LI)*	34.08	1.23	-	-
D *(LI)*	31.20	1.15	17	-2.88

5(b) shows the difference between pure Doppler estimates coming from all peers B, C and D and that coming from peer A. Finally, Fig. 5(c) is a histogram of the Doppler estimate discrepancies between the LI peers and the reference OS anchor peer A. The last figure shows that the maximum obtained difference is around 10 Hz which is relatively small and sometimes insignificant compared to a typical Doppler frequency step but that depends also on the integration time used.

The C/N_0 aiding estimated by each peer tracking GIOVE-A E1c pilot channel is shown in Fig. 6(a), where it can be seen that, unlike the anchor OS peer A which has a C/N_0 estimate of around 45 dB-Hz, peers B, C, and D show an estimate around 33 dB-Hz. This does not depend on the estimation method, and is mainly due to the OS view by peer A as well as the professional antenna provided to peer A, versus the patch antennas provided to the other peers. Fig. 6(b) further shows a comparison between the estimated C/N_0 values by peers A, B, and D versus that of peer C, which is the aided peer. We can see that peer A is not a good candidate to share its C/N_0 estimate, as it does not properly describe the aided peer C conditions. There should be a properly weighting mechanism which would result in an estimate closer to that of peer C, to further exploit peer A's estimate. Finally, Fig. 6(c) shows the corresponding histograms of the differences in terms of estimated C/N_0 values relative to the correct C/N_0 at the aided peer C, showing a Gaussian distribution of C/N_0 estimation errors.

Obtained C/N_0 results are also summarized in Table I.

IV. SIMULATION RESULTS

In this Section, different strategies properly exploiting the C/N_0 aiding information are analyzed and assessed by means of simulations computing the MAT, based on the Galileo E1 pilot signals in different scenarios (open sky or light indoor). A simple approach based on performing an average over all the available information from other peers will be compared with other approaches suitable to a hybrid system, able to estimate in some way its distance from other peers (e.g. performing terrestrial ranging measurements): in fact in this case, the aided peer can decide what are the closest peers, most likely to be in a similar environment, and then perform a weighted average on the C/N_0 estimates, giving a larger weight to the values obtained from the adjacent peers. In addition, the results obtained in a P2P scenario will be discussed with respect to an A-GNSS-like approach: as mentioned previously, the C/N_0 is

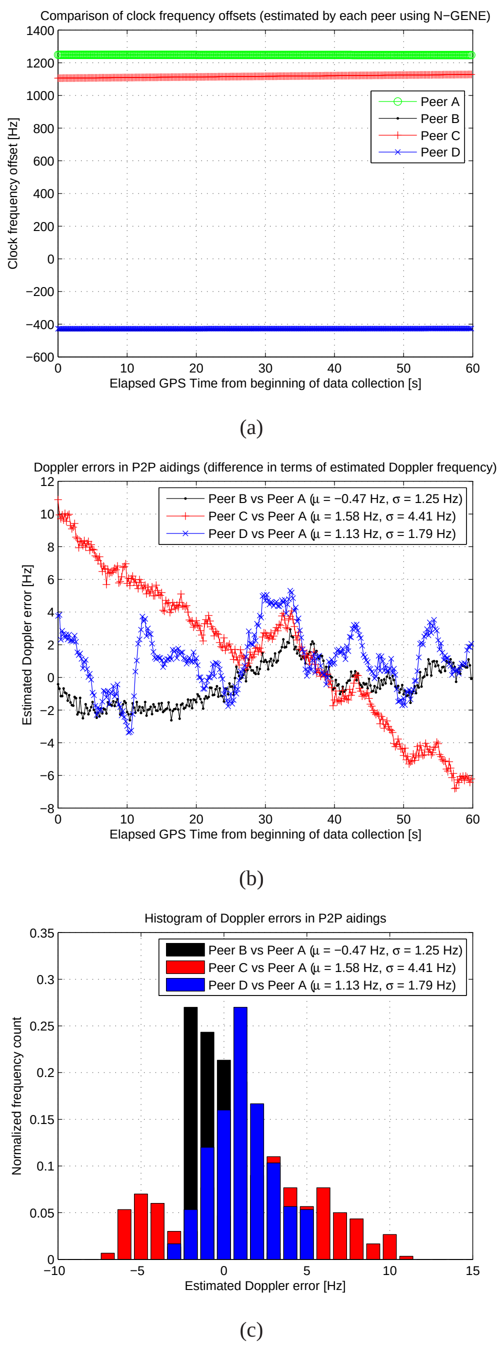


Figure 5. Comparison of clock frequency offsets (a), difference of estimated Doppler frequencies (b), and corresponding histogram (c) with respect to the reference OS anchor peer A , over a data collection of 60 seconds.

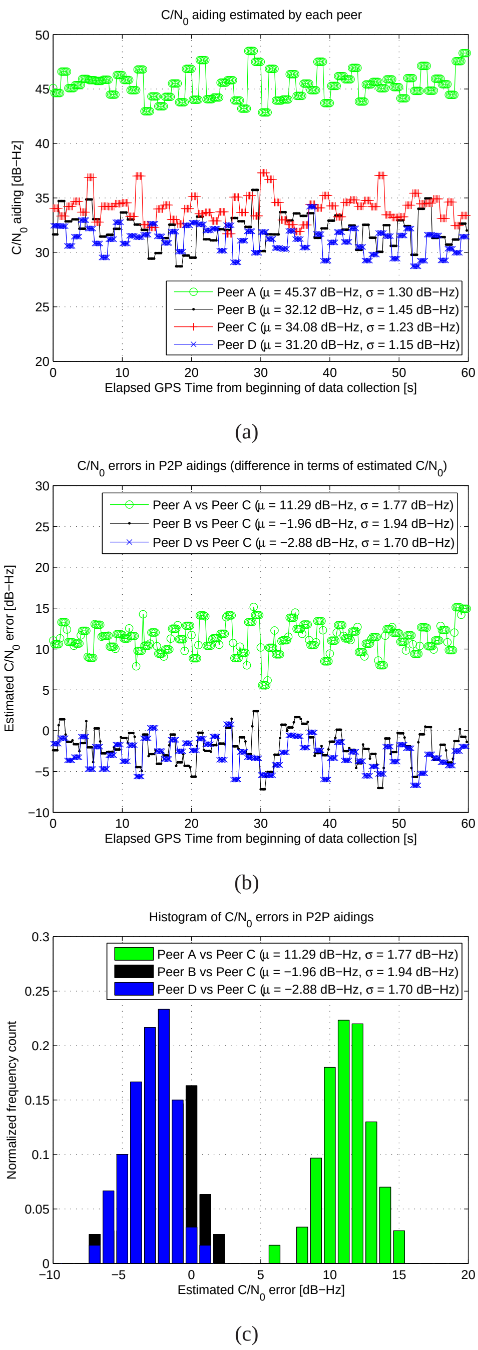


Figure 6. Comparison of C/N_0 aiding values estimated simultaneously by peers (a),difference of these values with respect to those estimated by the OS anchor peer A (b), and corresponding histogram over the first minute of data collection.

an assistance parameter but the procedure of exploiting it is not clearly defined in A-GNSS standards. A P2P aided acquisition strategy is thus expected to lead to some benefits in terms of acquisition performance with respect to a "blind" acquisition based on an A-GNSS-like approach (no information on C/N_0 is utilized).

A. Weighting strategies for exploiting P2P C/N_0 aiding

As previously outlined, in a P2P positioning system an aided peer can exploit information shared by other N aiding peers, by performing the following weighted average

$$\overline{A}_j = \sum_{i=1}^{N} \alpha_{ji} \hat{A}_{ji} \tag{5}$$

where:

- $\hat{A}_{ji}$ is the aiding value estimated by the i-th aiding peer, related to the signal of the j-th GNSS satellite;
- α_{ji} is the weighting coefficient corresponding to the aiding value $\hat{A}_{ji}$;
- $\overline{A}_j$ is the value estimated by the aided peer using the aiding values $\hat{A}_{ji}$ provided by N aiding peers.

This approach can be applied on all types of P2P aiding values foreseen at the physical layer (Doppler frequency, code delay and/or C/N_0). In detail, in case of C/N_0 aiding, (5) can be rewritten as

$$\overline{C/N_0}_j = \sum_{i=1}^{N} \alpha_{ji} \widehat{C/N_0}_{ji} \quad (6)$$

where $\widehat{C/N_0}_{ji}$ is the C/N_0 value estimated by the i-th aiding peer and related to the j-th GNSS satellite signal.

The weighting coefficients α_{ji} can be defined using different possible approaches proposed in [1] and discussed in the following.

1) **Uniform weights**:
The simplest approach is to perform an average on all available C/N_0 estimates from aiding peers and then use constant weights equal to

$$\alpha_{ji} = \frac{1}{N} \quad (7)$$

This approach is reasonable if all aiding peers have similar characteristics in terms of operative conditions and estimation capabilities (same hardware and same C/N_0 estimation algorithm), or in case that no information is available on their characteristics;

2) **Weights related to the quality of measurements**:
Another possible approach is to weight the available information depending on the reliability (in terms of accuracy and precision) of the estimates provided by each aiding peer. In fact the aiding peers, knowing their capabilities and their operative conditions, can broadcast a reliability parameter together with the estimated aidings. For example, if an estimate of the standard deviation σ_{ji} of $\widehat{C/N_0}_{ji}$ is available (estimated by the aided peer on the received aiding information or directly broadcast by aiding peers), it is possible to use a weighted average inversely proportional to σ_{ji}

$$\alpha_{ji} = \frac{1}{\sigma_{ji} \cdot \sum_{n=1}^{N} \frac{1}{\sigma_{jn}}} \quad (8)$$

where the summation at the denominator has been added in order to ensure a unitary sum of all the weights

$$\sum_{i=1}^{N} \alpha_{ji} = 1 \quad (9)$$

Another choice is to use fixed weights, depending on quality (accuracy, precision, reliability) of the available hardware (e.g. mass-market GNSS receivers or anchor peers, including professional receivers);

3) **Weights inversely proportional to the distance**:
If the distance d_i between the aided peer and each i-th aiding peer is known, it is possible to define the weights according to the following expression

$$\alpha_{ji} = \frac{1}{d_i \cdot \sum_{m=1}^{M} \frac{1}{d_m}} \quad (10)$$

where M is a subset of the N aiding peers with known distance from the aided peer ($M \leq N$).

4) **Weights inversely proportional to the distance squared**:
The knowledge of the distance between the peers can be also exploited by means of the following expression

$$\alpha_{ji} = \frac{1}{d_i^2 \cdot \sum_{m=1}^{M} \frac{1}{d_m^2}} \quad (11)$$

5) **Composite weights**:
It is also possible to compute the weights taking into account both the quality of measurements (strategy 2) and the distance between peers (strategy 3), computing weights that are inversely proportional to both σ_{ji} and d_i

$$\alpha_{ji} = \frac{1}{\sigma_{ji} \cdot \sum_{n=1}^{M} \frac{1}{\sigma_{jn}} \cdot d_i \cdot \sum_{m=1}^{M} \frac{1}{d_m}} \quad (12)$$

6) **Composite weights with distance squared**:
In a similar way, it is possible to combine weights from strategies 2 and 4, obtaining weights that are inversely proportional to σ_{ji} and d_i^2

$$\alpha_{ji} = \frac{1}{\sigma_{ji} \cdot \sum_{n=1}^{M} \frac{1}{\sigma_{jn}} \cdot d_i^2 \cdot \sum_{m=1}^{M} \frac{1}{d_m^2}} \quad (13)$$

7) **Closest peer approach**:
A simpler approach in order to exploit the knowledge of the distance between the peers is to select the closest peer (B, in our experimental scenario) and only use aiding values provided by it, discarding other information. The corresponding weights then can be defined as

$$\alpha_{ji} = \begin{cases} 1 & \text{if} \quad d_i = \min_i \{d_i\} \\ 0 & \text{otherwise} \end{cases} \quad (14)$$

It must be noticed that, apart from strategies 1 and 2, weighting approaches (from 3 to 7) require a knowledge of the topology of the cluster of peers, or at least an estimate of peers' distances. For example, in our experimental setup these distances were known (see Table I). In general the relative distance between peers can be estimated exploiting simple conventional radio ranging techniques on the terrestrial communication channel. For example, the aiding peers or the aided peer can measure the Received Signal Strength (RSS), the Time of Arrival (TOA), the Time Difference of Arrival (TDOA) or the Round Trip Time (RTT), using the communication network in order to perform range measurements. It is important to remark that this approach is different from hybrid positioning systems, able to compute the position of multiple nodes exploiting both terrestrial range measurements and GNSS signals. In our proposed P2P system the terrestrial ranges are only used by the aided peer in order to decide how to exploit aiding information, whereas PVT computations are still based on GNSS satellite info only (not hybrid). This approach is reasonable in case of terrestrial range measurements characterized by poor accuracy and precision with respect to GNSS measurements, although it represents a low complexity solution with respect to hybrid approaches.

On the other hand, the first two weighting strategies can be easily implemented without a knowledge of the network topology, but just averaging all available data (strategy 1) or estimating a standard deviation on received aiding values (strategy 2).

B. MAT Results exploiting P2P C/N_0 Aiding

The weighting strategies discussed in the previous Section have been validated and assessed by means of simulations based on real GNSS signal samples collected with our P2P experimental setup. A P2P aided acquisition of the GIOVE-A E1c pilot signal [10] has been simulated in post-processing, developing some MATLAB® scripts in order to exploit previously discussed aiding information. In detail, the developed aided acquisition engine is based on a flexible serial search and capable of searching few code delay bins and Doppler frequency bins around aiding values with an arbitrary coherent integration time (T_{int}, supporting also partial correlations of less than one secondary or primary code period) and non-coherent accumulations (L). After the computation of the search space (CAF), a conventional M of N detector has been implemented. In this way for each instant of time, starting from the empirical coherent integration time as defined in (4), and exploiting C/N_0 aiding ceiled over an integer multiple of 1 ms, the acquisition engine searches for a possible peak in the CAF and applies the M of N detector (in our setup $M = 3$ necessary success out of $N = 5$ trials) on subsequent chunks of signal.

In order to estimate the MAT, an approach based on an increasing T_{int} has been adopted. In detail, if the signal is not declared present by the M of N detector, a new repetition is performed and the algorithm doubles the current T_{int} value. After that, the acquisition engine searches again for the CAF peak and it continues to increase the T_{int} until the signal is correctly detected. Obviously, the Doppler step (δf) is decreased at each repetition, according to the well known empirical formula [11]

$$\delta f = \frac{2}{3T_{int}} \tag{15}$$

Assuming a constant Doppler range (fixed depending on the quality of Doppler aiding), this choice leads to an increased number of Doppler bins at each repetition and thus to a rapidly increasing computational burden in case of an inaccurate setup of the initial T_{int}.

Monte Carlo simulations have been carried out in order to assess the performance of the proposed weighting strategies, computing the MAT in terms of CPU time from MATLAB® simulations. In detail, our acquisition engine has been tested post-processing the raw samples collected by peer C (acting as the aided peer), weighting C/N_0 values estimated by other aiding peers at each repetition in order to set the initial T_{int} and repeating the signal acquisition every secondary code period (every 200 ms), for a total of 300 iterations (in 60 seconds of data). In addition, secondary code delay aiding (enabling the partial correlation approach and searching the code delay in a range of 2 chips) and Doppler aiding (using a Doppler range of ± 300 Hz around the expected Doppler frequency for the aided peer C) have been adopted during these simulations. Obtained results are then summarized in Table II where, in addition to the MAT (in terms of CPU time, in the last column), other data are reported: the mean difference ($\Delta C/N_0$) between the $\overline{C/N_0}_j$ estimate and the true C/N_0 at the aided peer (C), the mean T_{int} computed over all the Monte Carlo simulation, and the mean number of acquisition repetitions.

Table II
EXPERIMENTAL P2P C/N_0 AIDING RESULTS IN TERMS OF MAT (CPU TIME) USING DIFFERENT WEIGHTING STRATEGIES

Weighting strategy	**Mean Estimate** $\Delta C/N_0$ **Discrepancy w.r.t. Peer C** [dB-Hz]	**Mean final** T_{int} [ms]	**Mean number of repetitions** (doubling T_{int})	**Mean Acquisition Time** [s]
1. $1/N$	2.11	3.88	2.54	1.52
2. $\propto 1/\sigma$	2.07	3.95	2.41	1.65
3. $\propto 1/d$	-1.63	4.52	1.71	1.79
4. $\propto 1/d^2$	-1.97	4.54	1.63	1.70
5. $\propto 1/(\sigma \cdot d)$	-1.59	4.52	1.72	1.84
6. $\propto 1/(\sigma \cdot d^2)$	-1.51	4.49	1.75	1.88
7. **only** $min\{d\}$	-1.98	4.54	1.63	1.75

Using the aiding data collected from our experimental P2P setup, minor differences in terms of MAT have been detected, leading to a similar performance with all the weighting strategies. In fact they lead to a similar mean T_{int} over all the Monte Carlo simulations. Slightly better results in terms of MAT can be noticed only in case of strategies 1 and 2: this is because these two strategies give larger weights to the peer A (in OS conditions) compared to the weights given by the other weighting strategies. This leads to a larger expected C/N_0 and thus to a lower initial T_{int} (leading to a lower computational burden), but causes also a larger number of repetitions (doubling T_{int} at each repetition) when the M of N detector does not correctly detect the signal. In fact, in these two cases actual C/N_0 is about 2 dB lower than the value obtained averaging the aiding information, as can be noticed from the second column of Table II. In unfavorable conditions, for example assuming a lower C/N_0 (requiring longer T_{int}), a number of repetitions constantly larger than 3 would adversely affect MAT performance of strategies 1 and 2, leading to better results in other cases.

On the other hand, observing the mean number of repetitions (fourth column of Table II), it is possible to state that

Table III
EXPERIMENTAL RESULTS IN TERMS OF MAT (CPU TIME) USING AN A-GNSS LIKE APPROACH, ASSUMING DIFFERENT INITIAL COHERENT INTEGRATION TIME (T_{int})

Initial T_{int} [ms]	Mean final T_{int} [ms]	Mean number of repetitions (doubling T_{int})	Mean Acquisition Time [s]
1	3.94	2.68	1.79
2	4.48	1.98	2.05
4	5.69	1.40	3.04
8	8.16	1.02	5.50

better results are obtained with strategies 3 to 7. It must be noticed that in this case the strategy 7 (using only aiding information from the closest peer) leads to good results: in fact in this case the closest peer (B) was measuring the most similar C/N_0 to the actual value at the peer C (see Table I). This is a reasonable choice in light indoor conditions but, in unfavorable conditions (i.e. closest peer with a completely different C/N_0, e.g. due to the presence of walls or receiver failures) this approach would be more vulnerable than other approaches, which seem more robust exploiting (redundant) information from multiple peers.

C. Comparison between P2P C/N_0 Aiding and A-GNSS like approach

Further simulations have been carried out in order to compare the proposed P2P aided acquisition with respect to an "A-GNSS like" approach. In this case a simple "blind" acquisition, without C/N_0 aiding, has been simulated fixing an initial T_{int}, which is doubled until the signal is not correctly detected. Raw samples collected by the aided peer C have been used again, running a serial search over a search space with the same size of previous simulations (Doppler range equal to ± 300 Hz, code delay range equal to 2 chips) in order to have a fair comparison in terms of MAT. Obtained results for 4 different initial T_{int} are then summarized in Table III.

Increasing initial T_{int} from 1 ms to 8 ms, this A-GNSS like approach leads to a noticeable reduction in the number of repetitions: in fact, from previous P2P MAT simulations, the expected value of T_{int} was around 4 ms (see the third column of Table II), requiring multiple repetitions starting with $T_{int} = 1$. On the other hand, the MAT rapidly grows increasing the initial T_{int} and, apart from the first line of Table III, other cases always lead to worse MAT performance with respect to the P2P C/N_0 aiding approach (see Table II). This provides a preliminary demonstration of the advantages of the proposed C/N_0 aiding approach.

In order to further assess the benefits of this approach, additional simulations have been carried out considering different signal conditions. In detail, a realistic Galileo E1c signal, compliant with the current Open Service Signal In Space Interface Control Document (OS SIS ICD) [12], has been simulated in light indoor conditions (30 dB-Hz $\leq C/N_0 \leq$ 40 dB-Hz) taking advantage of N-FUELS [13], [14], a complete GNSS signal generation and analysis tool developed by our research group (NavSAS).

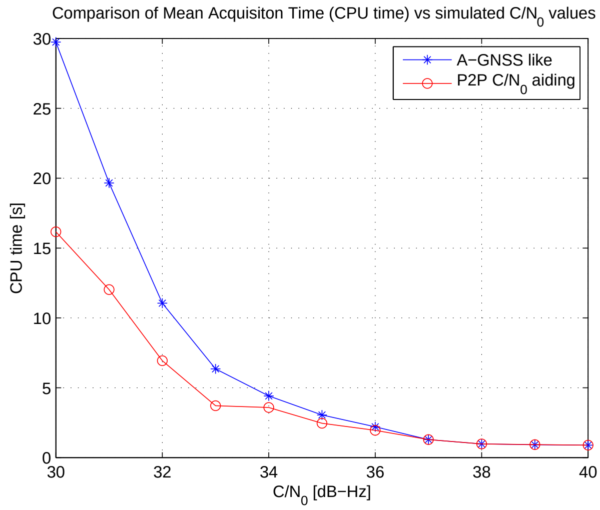


Figure 7. Performance comparison in terms of MAT for the A-GNSS like approach and the P2P C/N_0 aided acquisition, simulating a Galileo E1c pilot signal and varying the C/N_0

It must be noticed that current specifications for the Galileo E1 OS signal slightly differ from GIOVE-A E1 signals [10]: in fact its E1c pilot channels features a primary code with a length of 4 ms and a total code length equal to 100 ms (including primary and secondary codes), whereas the GIOVE-A E1c signal features a primary code length of 8 ms and then a total code length of 200 ms.

Previously described aided acquisition has been adapted to these signal specifications and then a new assessment of MAT performance has been carried out using the Galileo simulated signal and varying the simulated C/N_0. Also in this case the CPU time has been estimated by means of Monte Carlo simulations, performing 100 iterations for each C/N_0 value. In this case, the ideal C/N_0 aiding has been assumed (without introducing estimation errors from aiding peers). Obtained results are then shown in Figure 7, where the A-GNSS like approach (with a coherent integration of 4 ms) and the P2P C/N_0 aided acquisition are compared again.

It is worth mentioning that in order to perform a fair comparison, taking into consideration the possible benefits of C/N_0 aiding only, the A-GNSS like approach has been simulated exploiting secondary code aiding and a partial correlation approach just like the P2P paradigm. Obviously this is not feasible using current A-GNSS specifications especially in asynchronous networks like GSM.

As a final remark, it is possible to state that the P2P C/N_0 aiding provides larger advantages in terms of MAT in case of lower C/N_0 values: in fact, in this case the information from the aiding peers allows to properly setup the initial T_{int}, reducing the number of acquisition repetitions and then leading to a lower computational burden.

V. Conclusion

A novel P2P aided acquisition approach exploiting C/N_0 aiding has been presented in this paper. The proposed approach has also been validated and assessed using real data collected with an experimental setup in light indoor conditions and by means of simulations. The performance obtained has also been compared with an A-GNSS like acquisition strategy, showing the benefits of the availability of C/N_0 aiding information in terms of MAT.

It must be noticed that the proposed P2P collaborative acquisition approaches require a limited computational effort both at the aiding peers, for computing the aiding quantities, as well as at the aided peer, for exploiting obtained information. In fact, if the aiding peer is able to compute its position, the aiding quantities can be easily extracted from the PVT routines, obtaining clock frequency offset and drift, estimated Doppler frequency, C/N_0 and code delay for each satellite in view. On the other hand, the aided peer needs to perform few additional operations with respect to a stand-alone signal acquisition:

- It must compute a weighted average of the aiding information coming from other peers;
- In case of C/N_0 aiding, it needs to compute a formula for predicting the required coherent integration time (depending on the estimated C/N_0, the desired Signal-to-Noise ratio at the output of the correlators and the front-end characteristics).

In this way, exploiting the aiding information provided by aiding peers, the aided peer can significantly reduce the computational load needed for the aided signal acquisition with respect to a stand-alone signal acquisition. In addition, this P2P aided acquisition approach requires a similar computational burden with respect to a conventional A-GNSS approach: in this case the size of the acquisition search space is also reduced with respect to a full code delay and Doppler search. On the other hand, the availability of P2P C/N_0 aiding significantly reduces the MAT with respect to an A-GNSS like acquisition, especially in light indoor conditions.

As a final remark, this paper highlights the benefits only in terms of MAT computed taking into account a single satellite (GIOVE-A), however benefits in terms of Time To First Fix (TTFF) can also be foreseen in the P2P approach with respect to the A-GNSS like acquisition. As an example, the C/N_0 aiding info related to multiple satellites in view by the cluster of peers can be exploited in order to start acquisition at the aided peer from the satellites with higher expected C/N_0. This would lead to a reasonable reduction of the TTFF in indoor conditions, by allocating computational resources exclusively to the acquisition of satellites signals most likely to be received by the aided peer. Similar advantages can not be drawn from an A-GNSS approach since it does not provide useful info related to the expected C/N_0 at the assisted receiver vicinity.

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References

[1] R. Garello, L. Lo Presti, F. Dovis, D. Margaria, and J. Samson, *Sistema di posizionamento geo-spaziale cooperativo operante con sistemi di navigazione globale satellitare e reti di telecomunicazione wireless, relativo procedimento e apparato di posizionamento geo-spaziale*, Italian Patent Application N. TO2010A000718, Politecnico di Torino, Date of filing: August 30, 2010.

[2] L. Lo Presti, D. Margaria, and J. Samson, "A novel peer to peer aided acquisition strategy tailored to Galileo E1 receivers," in *52nd International Symposium ELMAR-2010, 15-17 September 2010, Zadar, Croatia*.

[3] F. Dominici, P. Mulassano, D. Margaria, and K. Charqane, "SAT-SURF and SAT-SURFER: Novel hardware and software platform for research and education on satellite navigation," in *Proc. of ENC GNSS 2009*, Naples, Italy, May 2009.

[4] F. van Diggelen, *A-GPS: Assisted GPS, GNSS, and SBAS*. Artech House, 2009.

[5] E. 3GPP, *Digital cellular telecommunications system (Phase 2+); Location Services (LCS); Mobile Station (MS) - Serving Mobile Location Centre (SMLC) Radio Resource LCS Protocol (RRLP)*, 3GPP TS 44.031 version 9.2.0 release 9, March 2010.

[6] E. Falletti, M. Pini, L. Lo Presti, and D. Margaria, "Assessment on low complexity C/N_0 estimators based on M-PSK signal model for GNSS receivers," in *Proc. of IEEE/ION PLANS 2008*, Monterey, California (USA), 5-8 May 2008.

[7] Product Info, Sparkfun, October 2010, URL: http://www.sparkfun.com/commerce/product_info.php?products_id=8238.

[8] SE4120L GNSS Receiver IC, SiGe, October 2010, URL: http://www.sige.com/files/SE4120L\%20Datasheet\%20Rev3p5.pdf.

[9] M. Fantino, A. Molino, and M. Nicola, "N-Gene GNSS Receiver: Benefits of software radio in navigation," in *Proc. of ENC 2009*, Napoli, Italy, 3-6 May 2009.

[10] Galileo Project Office, *GIOVE-A+B (#102) Navigation Signal In Space Interface Control Document, ESA-DTEN-NG-ICD/02837, Issue 1, Revision 1*, 2008.

[11] E. D. Kaplan and C. J. Hegarty, *Understanding GPS: Principles and Applications*, 2nd ed. Artech House Mobile Communications Series, 2006.

[12] European Union, *European GNSS (Galileo) Open Service Signal In Space Interface Control Document, OS SIS ICD, Issue 1*, 2010.

[13] E. Falletti, D. Margaria, and B. Motella, "Educational library of GNSS signals for navigation," *Coordinates*, vol. V, issue 8, pp. 30–34, August 2009.

[14] E. Falletti, B. Motella, G. Povero, and D. Margaria, "N-FUELS, a GNSS educational tool for simulation and analysis of a variety of signals in space," in *Proc. of ENC-GNSS 2010*, Braunschweig, Germany, 19-21 October 2010.