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On the Cooperative Ranging between Android Smartphones Sharing Raw GNSS Measurements

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***Abstract*—The combination of ubiquitous network infrastructure and the high density of powerful, interconnected mobile devices in urban areas is driving the rise of smart cities. In parallel, the availability of ultra-low cost embedded Global Navigation Satellite System (GNSS) has enabled several affordable Location Based Services (LBS). New chipsets supporting dual frequency and multi-constellation GNSS signals are reducing the gap between high grade and mass market device performances. Among these devices, Android smartphones represent valuable and affordable tools for many LBS in the early advent of Intelligent Transportation Systems and smart vehicular navigation. Mobile networks natively provide a multiplicity of connected devices, thus enabling a family of applications demanding for a communication channel among GNSS receivers. This paper experimentally validates a collaborative technique based on the exchange of raw GNSS measurements to retrieve the relative range between Android smartphones. Additionally, a framework for the exchange of data between smartphones is provided, allowing the application of such a computationally-efficient ranging methodology in a network of low cost mobile devices within a smart city framework.**

***Index Terms*—Global Navigation Satellite System, Android Raw Measurements, Double Differenced Ranging, GNSS Location Based Services**

I. INTRODUCTION

IN the last decade, the rise of the smart city paradigm has gained relevance in many Information and Communication Technologies (ICT) fields [1]. Among these, positioning and navigation technologies play a relevant role in smart transportation [1], thus providing a fundamental data for the monitoring and sustainability of urban mobility [2]. Global Navigation Satellite Systems (GNSS) play a vital role in such technologies guaranteeing the knowledge of the absolute position worldwide [3] under given conditions. The rising interest on multi-agent applications such as vehicle platooning, vehicle pooling and autonomous fleet is going to take advantage on the multiplicity of mass market GNSS receivers to retrieve also relative data (e.g. inter agent range measurements) which can improve navigation performance and situational awareness.

The majority of the location-based services related to the urban mobility relies nowadays on smartphones and their embedded ultra-low cost GNSS receivers. With the availability of GNSS raw measurements of Android smartphones since August 2016, the possibility to implement collaborative positioning and ranging algorithms among smartphones opened up. A remarkable amount of works in literature is present about range-based collaborative methods for positioning and navigation in robotics [4] and more recently such interesting approaches have been considered within a GNSS-only framework suitable for low-cost hardware [5]. Successful implementation of such with the ultra-low cost GNSS chipsets of Android smartphones are going to open a plethora of applications. For example, the impact of relative positioning on pedestrian navigation or the use of raw measurements for basic proximity indication of users among LBS. The shift in improvement of quality and features (multi-frequency, multi-constellation) of smartphone modules could extend similar applications to drones and service robotics as well.

The satellite-to-receiver range measurements are obtained at the early stages of the signal processing in GNSS receivers. Such measurements are affected by a known set of impairments which characterizes the satellite-based positioning problem (i.e. Ionopsheric delay, Tropospheric Delay, Relativistic delay, satellites clock bias, local clock bias) [3]. Previous works investigating the quality of these raw measurements in controlled [6], [7] and urban environments [8] have indicated their weakness to multipath and low-quality antenna effects [9], [10] as well. There has also been complex positioning algorithm implementation such as Precise Point Positioning (PPP) [11], [12] and Real Time Kinematic (RTK) Positioning [13] with such raw measurements and sub-meter level accuracy has been difficult to achieve.

The opportunity of implementing collaborative solutions based on raw pseudorange processing for positioning and navigation is attractive in ready-to-network devices like smartphones also considering the computational power of the current hardware setups. Considering the smartphone as an agent in the context of cooperative positioning literature, in this work the authors have implemented a double difference inter agent-ranging approach [14], [15] which induces the cancellation of common satellite and receiver clock errors affecting the smartphone pseudorange measurements. For such an approach, the feasibility of a low latency communication channel between the devices, dealing with the quality of the raw measurements and real time synchronisation of the devices at an early processing stage are the main challenges to be addressed. This work firstly presents the operational framework for two Xiaomi® Mi8 smartphones equipped with the chipset Broadcom® BCM47755 within the context of collaborative exchange of measurements between them and then the results of an inter-agent cooperative ranging algorithm based on double differencing.

The paper is organized in the following sections. After the introduction in Section I, a description of the methodologies implemented in the work are detailed in Section II. Section III presents the experimental setup and results of two tests, i.e. a short baseline static test and a zero baseline static test. Finally, conclusions are drawn.

II. METHODOLOGY

This methodology section details the procedure followed for implementation of the work using the Android raw GNSS measurements provided through the Android's Application Programming Interface (API) 24 for a set of devices equipped with Android 7 (Nougat) or later releases. The White Paper on using GNSS Raw Measurements on Android devices [16] released by the European Global Navigation Satellite Systems Agency (GSA) in early 2018 defined the raw measurements better for practical use and hence it has been referenced multiple times.

Considering the ubiquitous availability of wireless connections in smart cities (e.g. public Wi-Fi access points, cellular infrastructure), the addressed scenario considers the possibility to have a pair of Android devices sharing data connectivity for the exchange of data, as depicted in Figure 1.

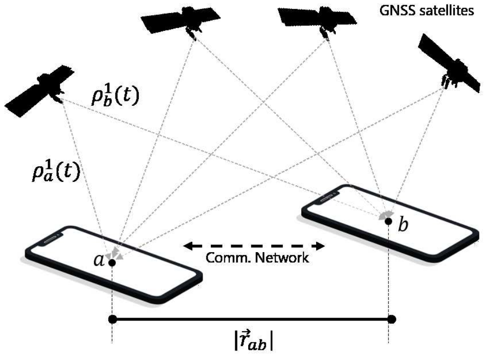

Fig. 1. Scheme of GNSS-based smartphone inter-agent ranging.

A. Data exchange

A communication channel is provided through IEEE 802.11b Wi-Fi connection exploiting a client-server service to which two smartphones are connected and registered throughout a predefined access point. Once an update of the measurements is reached by one of the two smartphones, it is sent to the server where it can be forwarded to any listening user. A transmitted packet of raw measurements information is offered by each smartphone and it is structured as in Figure 2.

```
---------------------------------------------------------------
          User ID            |             Timestamp          |
---------------------------------------------------------------
     Position Estimate       |      Position Uncertainty      |
---------------------------------------------------------------
                      Raw Measurements                        |
---------------------------------------------------------------
```

Fig. 2. High-level packet format for the exchange of raw measurements for cooperative positioning applications.

It is conceived as a multi-cast packet in which the user ID is a unique identifier for the sender. A position estimate and the associated uncertainty is also considered for potential integration algorithms including the collaborative measurement or the knowledge of neighbours locations themselves. The main payload field, named *raw measurements*, contains the satellite-to-agent estimated ranges and the Doppler measurements (provided by the GNSS unit of the smartphone) that can be used by neighbours for the steps described hereafter. Raw pseudorange measurements, identified by the letter ρ as shown in Figure 1, are computed by estimating the time of travel of transmitted signal, according to [16]. Such an information is provided as raw data by the Google® Android API. The Doppler measurements identified by the letter ϕ are instead typically provided by the Frequency-locked Loop at the acquisition stage of the receiver [3].

B. Synchronization of Measurements

Two separate measurements can be aligned with a satellite signal Time of Week (ToW) transmission information, however the actual pseudorange and subsequent raw measurements are not retrieved at a common GNSS or Global Positioning System (GPS) time of both the receivers. The time-consistency of the asynchronous measurements is hence achieved by exploiting a Doppler-based compensation technique [17] which facilitate the merger of asynchronous pseudorange measurements into double-difference based ranging measurements following

$$\rho(t+\Delta t) = \rho(t) + \Delta t \cdot \lambda \cdot \phi(t) \tag{1}$$

where λ is the carrier wavelength according to the investigated signals and constellations. The Doppler measurement of a given satellite observed at time t provides an estimate of the pseudorange change rate and can therefore be used to predict the pseudorange in $t+\Delta t$. The correction holds if the relative movement between receiver and satellite is constant and it can be assumed true dealing with static or moderate dynamic of the receiver. The choice of Δt is operated according to the pseudorange estimation method (common receiving time or common transmitting time) [18]. Several solutions for the computation of the range starting from Double Difference have been explored in literature. As an example of application, a plain double difference ranging has been used as reported in the following [19].

The pseudorange generation method used by the android chipset is the common reception time method where all pseudoranges in an epoch and in subsequent epochs are calculated relative to the very first satellite signal to arrive at the first epoch of observation. Theoretically using the raw smartphone clock measurements `BiasNanos` (receiver clock's sub-nanosecond bias), `DriftNanosPerSecond` (receiver clock drift) and `TimeOffsetNanos` (Time offset at which the measurement was taken in nanoseconds), the accurate GPS time of pseudorange measurement can be computed and hence synchronisation can be achieved. The definitions of these measurements are stated in [16]. However, all three measurements are currently unavailable with the BCM47755 chipset for the Xiaomi Mi 8 phone and the alternative was either the use of the clock bias output of a Position, Velocity and Time (PVT) solution for each phone or take use of the `FullBiasNanos` raw measurement provided by the phone. The latter is the direct bias measurement given at each epoch by the smartphone after it has estimated the GPS time through the cellular network and/or the internal PVT solution within the android software [16]. Using it negates the need for a PVT computation for the phones saving valuable processing time and computational power. Thus this allows for the formation of the Δt parameter (as in equation (1)) between the two receivers to be used in a Doppler based adjustion technique.

C. Relative Range measurements by Double Differencing

When a good synchronization of the measurements is provided, single differences among pseudorange measurements allow to remove the clock biases of the satellite constellation. As a further step, double differences cancel out the user clock bias thus leading to accurate range computation using GNSS observable data only. The use of differential GNSS can rely also on the availability of multi-constellation environments. A single difference can be defined between two GNSS users tracking a common satellite, as

$$s_{ab}^{j}(t) = \rho_{a}^{j}(t) - \rho_{b}^{j}(t) - \Delta\rho_{ab}(t) + \Delta b_{ab}(t) + \Delta\epsilon_{ab}(t) \quad (2)$$

where Δb_{ab} indicates the bias difference due the users clock offsets and $\Delta\epsilon_{ab}$ includes all the non-common noise related to each satellite-receiver pair. When the same couple of satellite i and j is visible to both the receivers, a double difference measurement can be obtained as difference of two single differences

$$\begin{aligned} d_{ab}^{j}(t) &= s_{ab}^{j}(t) - s_{ab}^{i}(t) \\ &= \left[\vec{e}^{i} - \vec{e}^{j}\right] \cdot \vec{r}_{ab}(t) + \left[\Delta\epsilon_{ab}^{i} - \Delta\epsilon_{ab}^{j}\right]. \end{aligned} \quad (3)$$

On identifying a satellite as a reference, the computation of the range vector, $\vec{r}_{ab}$, can be obtained by solving

$$\mathbf{d}_{ab} = \mathbf{H}\vec{r}_{ab} + \epsilon \quad (4)$$

where $\mathbf{d}_{ab}$ is a column vector of double differences w.r.t. the shared satellites and $\mathbf{H}$ is defined with respect to the reference satellite by differentiation of the steering vectors $\vec{e}$, as follows

$$\mathbf{H} = \begin{bmatrix} \left[\vec{e}^{1}(t) - \vec{e}^{0}(t)\right]^{T} \\ \left[\vec{e}^{2}(t) - \vec{e}^{0}(t)\right]^{T} \\ \vdots \\ \left[\vec{e}^{S-1}(t) - \vec{e}^{0}(t)\right]^{T} \end{bmatrix}. \quad (5)$$

The range measurement is hence obtained in a Weighted Least Squares (WLS) solution as the norm of the displacement vector $\vec{r}_{ab}$, as

$$\vec{r}_{ab} = \left(\mathbf{H}^{T}\mathbf{R}_{d}\mathbf{H}\right)^{-1}\mathbf{H}^{T}\mathbf{R}_{d}\mathbf{d}_{ab} \quad (6)$$

where $\mathbf{R}_{d}$ is the error covariance matrix associated to the range measurements, whose terms can be retrieved directly through the Android API. Inter-agent ranges are expected to be sufficiently uncorrelated with the measurements used for the further PVT computation so that they can bring further information about the users positions, still according to geometry and quality of the initial estimated position [5].

The example in Figure 3 shows the comparison of range estimates obtained at each epoch by means of double differencing of simulated raw measurements according to the methodology in Section II, computed between two static GNSS software receivers with a zero baseline. One is a non-weighted asynchronous Double Difference Range (DDR) and the other being the Doppler compensated Weighted Double Difference Range (DDR-W). The measurement noise variance for the simulations is the nominal standard deviation of 6.7 meters (m) as mentioned in [3].

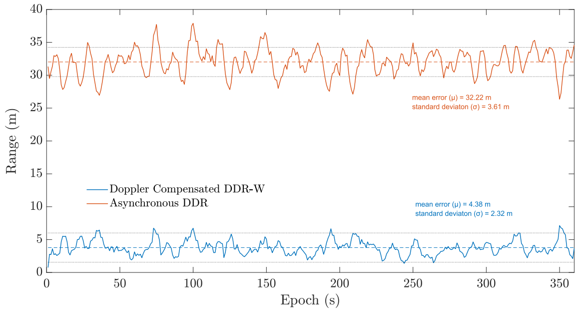

Fig. 3. Range bias compensation in DDR between two static receivers by means of raw Doppler measurements with simulated GNSS signals (no multipath, 6 GPS satellites).

It can be noticed that while the benefit induced by the weighting strategy is limited to a small standard deviation reduction, the compensation of the time misalignment through raw Doppler measurements is fundamental to mitigate the bias in the inter-agent range computation.

III. EXPERIMENTAL SETUP AND RESULTS

This section presents a collection of relevant results about the quality of the inter-agent measurements. According to the nomenclature in GNSS literature, the two experiments are classified w.r.t. the length of the true displacement vector, also known as baseline.

A. Short Baseline Static Test

10-minute static datasets were collected in the campus of the Politecnico Di Torino (45.062099° N, 7.663334° E), Torino, Italy, with two Xiaomi Mi 8 devices 20 meters apart, on the 22nd of February 2019 in a sub-urban sky condition. Android raw measurements were collected through the communication network IEEE 802.11b Wi-Fi connection and processed through an internal version of the open source MATLAB 'gps-measurement-tools' software [20]. The Xiaomi Mi 8 offers the option to turn off the 'duty cycle' of the device through its developer mode and that was an added consideration during the data collection. Duty cycle is a power saving function of most smart devices where commonly, the hardware clock is switched off for a fraction of every second resulting mainly in carrier phase tracking discontinuity [16]. Although multi-frequency, multi-constellation measurements were recorded, only GPS L1 (1575.42 MHz) signal measurements were processed for initial validation. The use of GPS only does not imply a lack of generality since the same procedure can be applied to the other constellations. Furthermore, multi-constellation implementation is also possible once the user clock bias with respect to each constellation has been removed (i.e. a solution has been obtained).

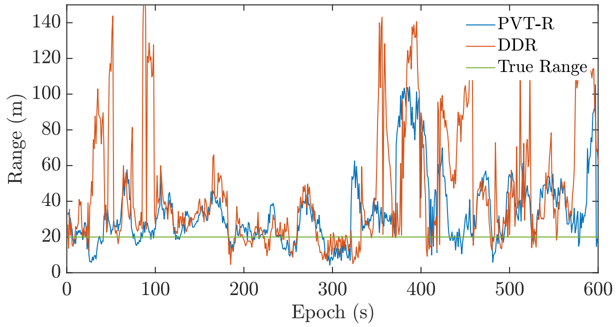

Fig. 4. 20 m baseline test with DDR and PVT-R comparison.

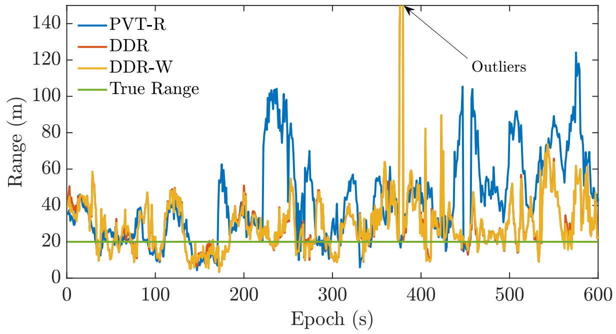

Fig. 5. 20 m baseline test with DDR, DDR-W and PVT-R comparison.

The unreliable quality of smartphone raw measurements is a hindrance due to poor antenna performance, hence a 'real-time' satellite filtering strategy as well as a weighted solution was adapted based on the parameter `ReceivedSvTimeUncertaintyNanos` [21]. Three different relative ranges between the phones were compared; DDR and DDR-W (both Doppler compensated) and the Euclidean Range (PVT-R) calculated after standalone-PVT solution computation of the receivers individually. For the standalone solution, some satellites were excluded for a fair comparison with the filtering strategy.

TABLE I
COMPARISON OF THE QUALITY OF GNSS-BASED RANGES

Test with two Xiaomi Mi-8 devices		**600 s interval** PVT-R	DDR	DDR-W
DATASET 1	σ (m)	19.4	12.2	12.1
	μ (m)	10.5	9.9	7.6
DATASET 2	σ (m)	9.5	8.7	8.6
	μ (m)	8.4	5.4	5.4
DATASET 3	σ (m)	18.2	10.4	10.2
	μ (m)	24.7	6.3	5.8

Figure 4 shows the basic comparison of the ranges without taking into consideration the quality of the pseudoranges and it is seen that both the ranges are noisy with the PVT-R being slightly better. On filtering out poor measurements, significant improvement to the DDR and DDR-W ranges is seen in Figure 5 and it is in general better than the PVT-range, barring a few outliers which the weighted solution fails to take account of. The mean GDOP value was around 2 and 2.5 before and after filtering respectively. This observation is consistent with the other dataset measurements and in dataset 3 (5-minute observation), the improvement in the mean error is 4-5 times higher. Table I presents a comparison of the quality of the GNSS-based ranges in the different datasets with respect to the standard deviation (σ) and mean error (μ). There is still a significant bias and noise present in the measurements due to the uncorrelated noise being quadrupled after double differencing, as shown in [22], but this relatively superior range output produced taking advantage of Android raw measurements only without the PVT computational burden opens an interesting application of cooperation among Android smartphones.

B. Zero Baseline Static Test

Following this, the presented strategy was also applied to a simple zero-baseline test performed on the rooftop (open sky condition) of the Politecnico Di Torino campus, Torino, Italy (45.063780° N, 7.662003° E) by placing two Xiaomi Mi 8 Pro phones next to each other on the 15th of March, 2019.

In addition to filtering of the satellites, the Doppler compensated pseudoranges for DDR and DDR-W were further smoothed based on their Doppler ranges [23] and there was a significant quality enhancement with the near complete removal of a bias seen in the PVT-R as seen in Figure 6. The mean error and standard deviation of the latter was 6.6 m and 3.1 m respectively. In comparison for the DDR and DDR-W, the mean errors were 1.5 m and 1.4 m respectively with the standard deviations being 1.2 meters for both. The mean GDOP value was around 2.5 during the test with an average of 5 satellites considered after filtering out the poor measurements. The smoothing strategy has not been implemented to be robust yet for urban or sub-urban sky conditions, hence further development has to be done.

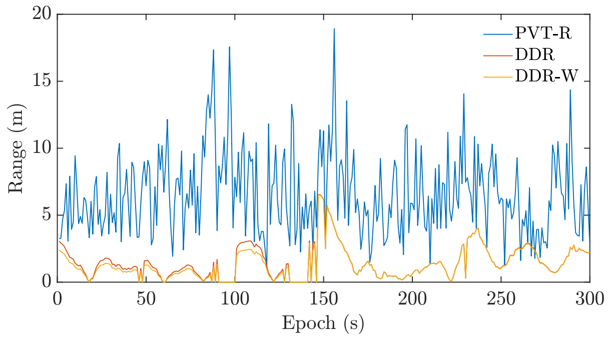

Fig. 6. DDR and DDR-W applied on smoothed pseudorange measurements, compared to PVT-R.

IV. CONCLUSIONS

With this work, the authors have firstly demonstrated the successful data exchange of raw GNSS measurements through the IEEE802.11b Wi-Fi connection in Android smartphones. Further, the superior performance of such raw GNSS measurements for relative ranging when compared to stand alone positioning based solutions has been validated. This not only provides a platform for localised exchange of data between Android smartphones, but also a useful computationally efficient ranging methodology in a network of smartphones.

The implementation of the aforementioned double differenced algorithm is strategically carried out in smartphones taking advantage of its various GNSS raw measurement outputs. The algorithm is to be expanded to include robustly smoothed pseudoranges, single differencing methods and multi-constellation and multi-frequency measurements while a more controlled environment analysis is also desired. There is a demonstrable increase in interest of the application and positioning performances of Android raw measurements since its advent and the hardware quality of the smartphones GNSS modules are only getting better. This bodes will with the presented research and opens the pathway for more complex cooperative approaches between smartphones with the framework demonstrated in this work.

V. ACKNOWLEDGEMENT

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