An Analysis of Positioning and Map-Matching Issues for GNSS-Based Road User Charging

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Abstract— **The time for new paradigms for pay-per-use road use charging (RUC) has come, and it is still unclear whether or not current Global Navigation Satellite Systems (GNSS) supply reliability enough to lead the technological deployment. It is the general belief for RUC stakeholders that GNSS is the most flexible and cost-efficient technology for such a large deployment. However, the German experience of Toll Collect shows that GNSS must be strongly complemented by road side equipments to reach the necessary charging reliability standards. This paper analyzes some significant points of a GNSS-based RUC schemes, with a special emphasis on relevant map-matching issues. This analysis is complemented by our proposals for supporting GNSS with aiding onboard sensors and maps, and discussions about how the charging reliability may result affected by that. The paper finishes with a summary of the most remarkable conclusions achieved in our investigations.**

I. INTRODUCTION

The payment methods for road usage have received a great attention during the past two decades. More recently, new advances in ICT (information and communication technologies) have encouraged researchers all around the world to develop automatic charging systems aiming at avoiding manual payments at toll plazas while enabling administrations to deploy charging schemes capable to reduce congestion and pollution. The recent application of Global Navigation Satellite Systems (GNSS) on these charging platforms can present important advances, and the research community in ITS (Intelligent Transportation Systems) is aware of this.

During the past years, dedicated short range communications (DSRC) have been a key technology to automate the charging process on roads. By means of an on-board transceiver, the vehicle is detected when passing toll points. In real deployments there are usually speed limitations, since the communication channel between the on-board unit (OBU) and the road-side unit must be maintained for a while to allow the exchange of charging data. However, DSRC-based solutions present important problems such as the cost of deploying road-side equipments when more and more roads want to be included in the system (a scalability problem) and a lack of flexibility for varying the set of road subject to charge. In this context, GNSS is lately considered as a good alternative. Essentially, GNSS-based RUC use geographic positions to locate vehicles in charging areas or roads, and this information is sent to the operator's back office to finally create the bill. The European Union is promoting the European Electronic Tolling Service (EETS) [1] as an interoperable system throughout Europe on the basis of satellite positioning (GNSS), mobile communications using cellular networks (CN) and DSRC technology, using microwave 5.8 GHz band.

Several standardizations actions concerning electronic fee collection have been already considered by the European Commission, such as the security framework needed for an interoperable EETS, to enable trust between all stakeholders, and the definition of an examination framework for charging performing metrics.

Currently, some of the most important deployments of electronic RUC already use GNSS. In Switzerland, the LSVA system (also known as HVF for the English acronym of Heavy Vehicle Fee) complements a distance-based model based on odometry and DSRC check points with GPS measurements. The role of GNSS in the German Toll Collect system is more remarkable, since GPS positions are used to identify road segments. Nevertheless, other extra mechanisms are used to assure the vehicle charging in places where the GPS accuracy cannot guarantee the road identification. This problem has been analyzed for a potential deployment of a GNSS-based RUC in Denmark [2], comparing the GPS performances obtained in 2003 and 2008. Although availability and accuracy problems limited the usage of GNSS for RUC in the city of Copenhagen in 2003, most recent results show that advances in receiver technology and updates in the GPS system make it possible to consider the usage of GNSS in 2008. This study supports this thesis primarily on the rise of the number of satellites in sight. In our opinion, these results must be taken with caution, since it is not analyzed in the experiments how many of the satellites in view are affected by non-line-of-sight (NLOS) multipath. In The Netherlands, the plans for creating a distance-based charging system for all vehicles on all roads also consider GNSS as the potential base technology [3].

As it has been aforementioned, the accuracy of the position

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estimates is one of the main concerns towards the application of GNSS for RUC. It is necessary to provide a confidence level which assures that the estimate of the vehicle location is close enough to the real one with a specific high probability. This is the reason why the integrity concept is receiving a great attention in GNSS-based RUC these days [4]. Per contra, the importance of the map-matching process is many times forgotten. When users are charged in accordance with the infrastructure used, the identification of charging objects (e.g. the road segment) is of key importance for the system. Even when the tariff scheme is not based on charging objects, the usage of additional digital cartography can be useful to improve the performance of the navigation system.

The rest of the paper goes as follows. After presenting some important aspects of GNSS for RUC in Section II, more remarkable performance requirements and problems are analyzed in Sections III and IV. Next, some common methods for map-matching used in RUC are introduced. Section VI shows how the position integrity, computed by an hybrid navigation system, and the additional support of digital cartography when available can improve the performance of a GNSS-based RUC. Section VII concludes the paper.

II. GNSS FOR ROAD USER CHARGING

In GNSS-based RUC, information from the GNSS sensor is used to locate vehicles at charging places. The use of GNSS as the main positioning technology to charge users for the road usage, has several benefits related to flexibility and deployment costs: A minimum set of road-side units would be needed, mainly focused on enforcement purposes; OBU capabilities can be as simple as collecting GPS positions and sending them to a processing center, or as complex as calculating the charge and reporting payment transactions; a software-based OBU allows for software updates, reducing maintenance and system upgrade costs; GNSS sensors are cheaper and cheaper, and its performance is increasing; cellular networks which is the main communication technology considered has a wide coverage, more than enough data rates for RUC, and decreasing costs which are also subject to agreements with operators.

Due to the flexibility of GNSS-based RUC, a multitude of approaches can be designed to charge users. As main distinction factor, GNSS-based RUC solutions can be classified according to the tariff scheme used in the system. There can be distinguished three tariff schemes according to the literature [5], [6].

a) Discrete charging: In this case toll events are associated to the identification of road objects subject to be charged. This group includes single object charging (bridges, tunnels, etc.), closed road charging on certain motorway segments, discrete road links charging, cordon charging, or zone presence charging.

b) Continuous charging: The tariff is calculated based on a cumulative value of time or distance. Distance-based charging and time in use charging are included in this group.

c) Mixed charging: A combination of aforementioned approaches is used. An example of this tariff scheme is charging for cumulative distance or time considering a different price for each road segment.

III. PERFORMANCE REQUIREMENTS FOR GNSS-BASED ROAD USER CHARGING

A clear definition of the performance requirements for a road user charging system is needed for two main reasons. First of all, the industrial consortiums that apply for a deployment must be equally evaluated and the final choice must be based on the goodness of each solution according to some previously established performance needs. Secondly, the interests of users and authorities must be guaranteed.

The description of the performance requirements depends on the final charging scheme. Since it is likely that any final charging scheme is based on a combination of continuous and discrete ones, let us analyze briefly both cases here.

For a discrete charging scheme, there are only four possible cases: a correct detection (CD), a correct rejection (CR), a missed detection (MD) and a false detection (FD). Last two cases cause undercharging and overcharging respectively. Because the consequences of a MD and a FD are not the same, it is necessary to analyze these effects separately, and not by a single index of overall correct detection rate. Therefore, there must be two different performance requirements to avoid overcharges (for users) and to ensure revenues by avoiding undercharges (for authorities). Furthermore, it must be decided whether the requirements must be satisfied any time, for any trip in any scenario and under any circumstance, or it is enough if the average and some statistical parameters show that the overall errors or overcharge and undercharge are within desirable thresholds. The latter may lead to persistent errors in the bills of some users who repeatedly drive trajectories not well covered by the RUC system, due for example to bad satellite visibility conditions in the area. These special cases should be handled as exceptions, because it cannot be accepted that a system does not treat fairly every user.

Analogously, for continuous schemes also two parameters are needed to protect the interests of both users and service providers. Inspired by the notation of the navigation community [7], some authors introduce the concepts of charging availability and charging integrity [15]. Charging availability can be defined as the probability that the charging error is within a desirable error interval. While, by definition, this parameter protects the interest of both the user and the toll charger because it covers positive and negative errors (overcharges and undercharges respectively), its main mission is to provide the toll charger with a level of warranty that the user will pay for the road infrastructure usage. On the contrary, charging integrity can be defined as the probability that the error is not over an upper limit; this is, that the user is not overcharged, and its value must be more restrictive than the charging availability (this is why we claim that the main objective of charging availability is to protect the interests of the authorities).

Since the charging integrity cannot be compromised, the developers must find a way to be aware of the reliability of every charge. In case of reasonable doubt, it is preferable not to charge, rather than to charge wrongly. For this reason, some integrity indexes must be calculated to verify the certainty of the charges. If integrity indexes inform of a possibly unsafe charge and the user is finally not charged, the probability associated to charging availability becomes smaller, but not the one linked to charging integrity. On the contrary, if the user is charged wrongly, both values of probabilities become smaller and the charging availability and integrity are compromised. The tuning of the integrity indexes must be done in such a way that it satisfies the needs regarding availability and integrity. If this tuning cannot be found, the system is incapable of providing the aimed level of reliability and it must be disregarded. Although a good estimation of the integrity parameters is crucial for the developers, this aspect must neither appear in the definition of performance requirements, nor being tracked during the evaluations. It must be understood only as an internal parameter that eventually affects the charging availability and integrity.

Finally, one must bear in mind that the performance indexes coming from both discrete and continuous schemes must be transformed into a unique performance parameter, based for example on the impact of each error (discrete or continuous) on the eventual charge. This is necessary since despite the fact that the proposals coming from the industry could be based on different charging schemes, there must be a possible direct comparison for all of them and the final system must be seen as a sole charging system independent of the scheme particularities. Furthermore, the integration of continuous and discrete performance indexes turns into essential for mixed charging schemes.

IV. PROBLEMS OF GNSS-BASED RUC

Although there could be problems derived from the communication channel used to send charging information to service centers, the main drawback of GNSS-based RUC is the performance of the GNSS sensor. The lack of availability of the GPS signals at places where there is no line of sight with satellites is a remarkable problem in urban canyons, tunnels or mountain roads, for instance.

A research assignment demanded by the Dutch Ministry of Transport, Public Works and Water Management [16] focuses on the accuracy and reliability of distance and position measurements by GNSS systems. The trials involved 19 vehicles during one month, and concluded that during the 13 % of the travelling time there was no valid GPS position, although the overwhelming part of the unavailability was due to time to first fix (TTFF). Highly related to this, the continuity of the GPS services is also dependent on military decisions of the US government, since GPS is not a pure-civil navigation system. Moreover, the accuracy of the position estimates, although it has been improved thanks to enhancements in the space segment and in the receiver technology, is still not fully reliable to decide whether or not a user must be charged for supposedly using a road. Although some performance problems can be compensated (satellite clock bias, signal propagation delay, etc.), others such as multipath effects in the user plane are not yet modelled and degrade the accuracy in urban canyons. All these problems can reduce the performance of a liability-critical service such as RUC. The analysis made in [16] for GNSS positioning accuracy shows that its 95% level is 37 m. Nevertheless, this number must be taken with caution when considering RUC applications, because many other factors apart from the GPS inaccuracies themselves can affect this result, such as inaccuracies in digital maps or errors in the map-matching process.

The consequences of the positioning errors in the system performance would not be so severe if current GNSS devices would provide a fully meaningful value of the reliability of the positioning: its integrity. In this case, although the performance availability of the system may diminish, its integrity remains and users would be protected against overcharge. It is then up to the authorities to decide whether or not the performance availability is good enough to deploy the system, in other words, to ensure the revenue of the investment. However, current integrity values provided for GNSS devices are unappropriate.

An approximation to provide integrity in GNSS-based positioning is given by the Receiver Autonomous Integrity Monitoring (RAIM) algorithm. This technique, initially created for aerial navigation, is based on an over-determined solution to evaluate its consistency, and therefore it requires a minimum of five satellites to detect a satellite anomaly, and six or more to be able to reject it [8]. Unfortunately, this cannot be assumed in usual road traffic situations, especially in cities [9]. In addition, the RAIM method makes the assumption that only one failure appears at one time, something feasible in the aerial field, but not in road scenarios: it is usual that several satellite signals are affected by simultaneous multi-path propagations in an urban area.

Satellite Based Augmentation Systems (SBAS), such as EGNOS (European Geostationary Navigation Overlay Service) or WAAS (Wide Area Augmentation System), offer also integrity calculation. By means of the information of the GNSS operational state, broadcasted by GEO satellites, it is possible to compute a parameter of system integrity [10], [11]. However, this approach does not consider local errors such as multipath, which are of key importance in terrestrial navigation. Multipath effects violate the assumption of only one failure at once.

Due to these problems, in the last years some authors suggest new paradigms to estimate the system integrity [4], [12]. In concrete, [4] shows an interesting approach for integrity provision based solely on GNSS that obtains interesting results.

V. MAP-MATCHING FOR ROAD USER CHARGING

In tariff schemes where the user is charged for driving along a road stretch or using a certain road infrastructure, the map-matching algorithm plays an essential role. However, as far as the authors know, there is not enough information in the literature about these algorithms applied to RUC, since

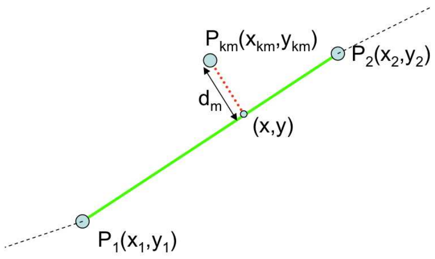

Fig. 1. Point-segment distance in map-matching.

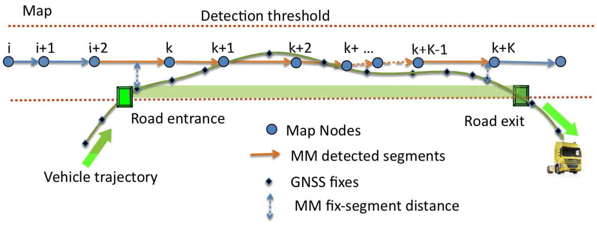

Fig. 2. Correct operation of map-matching using point-segment distance.

current approximations are inside proprietary RUC solutions. This is identified as a problem towards standardization and calibration, apart from making more difficult the comparison between different algorithms.

The most common algorithm used in map-matching is considering the distance between the vehicle location and the nearest road segment. In this way, apart from the GNSS sensor, digital information about the road network is necessary. Fig. 1 illustrates this algorithm, based on the point to segment distance. An ENU (East, North, Up) cartesian coordinate system is considered, and the computed fix for the vehicle at moment t_k is denoted as $P_{km} = (x_{km}, y_{km})$. The algorithm has three main steps:

1) Search for a road segment near the vehicle position, with coordinates $P_1 = (x_1, y_1)$ and $P_2 = (x_2, y_2)$.
2) Calculate the distance d_m between P_{km} and the segment.
3) If current segment is closer than previous segments to the position estimate, take it as a candidate.

An scenario which illustrates a correct operation of the previous algorithm is shown in Fig. 2. The vehicle is correctly detected at the entrance and exit points in the charing link, and the K road segments pertaining to the stretch are also identified. However, in real complex scenarios, GNSS performance problems can imply misdirection of road segments and overcharging or undercharging.

An extra problem appears when vehicles drive near a charge link but the real driving road is not present in the digital cartography. An umbral factor to detect roads can help to solve this problem. Fig. 3 illustrates this solution over a distance-based charging scheme. It considers a 57 km travel of a vehicle along a mix of charge and free roads. The last ones were selected from the available secondary roads which are parallel to the main highway. For this case, a threshold of 10 m was found useful to solve the misdetection problem. According to our large number of tests on Spanish roads, this technique and a suitable threshold can be useful to solve the problem of non-digitalized parallel secondary roads. However, further mechanisms are necessary to assure the correct identification of roads under potential GNSS performance errors and when more than one applicable road require a disambiguation decision.

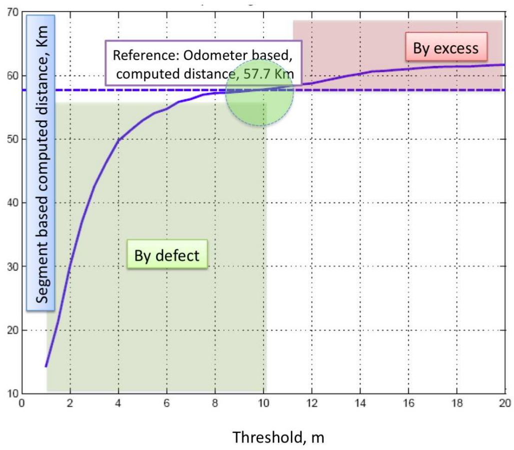

Fig. 3. Undercharging and overcharging and the selection of a threshold value in map-matching.

VI. COMPLEMENTING GNSS IN RUC

According to the current literature and our own tests, at its present form, the simplest approach for GNSS-based location for RUC based on single GPS positioning or GPS positioning map-matched to a standard digital cartography is not capable to ensure the demanded levels of performance availability and integrity. To enhance these results, standard positioning can be aided by different sensors in both the onboard equipment (OBE) and the road side equipment (RSE). We analyze in this section the main benefits of GNSS aided location with OBE sensors and maps for the purpose of RUC and its effect on the provision of performance integrity, with a especial emphasis on map aided road user charging.

A. *Aiding Positioning Sensors*

Many advanced positioning systems employ a minimum set of a GNSS receiver, an odometer for speed values and a gyroscope for heading estimates. This configuration presents a good balance between performance and budget. During GNSS outages, the dead-reckoning system keeps estimating positions. The magnitude of position drifts depends primarily on the quality of the aiding sensors, but also on the skills of the algorithm used for sensor integration. Some interesting examples of GNSS-aided positioning in either loose or tight coupling modes can be found in [17]–[19].

Aiding positioning supports RUC because as long as the quality of the position is kept and guaranteed, the road user charging system can stay available. Another advantage comes from the fact that hybridization algorithms smooth the noisy trajectories generated by the GNSS positions and represent more realistically the movements of vehicles, what can be useful to eliminate to some extent the overcharge accumulated in distance-based charging schemes that employ the GNSS positions to estimate the distance. It is also possible to compare the odometer distance and the GNSS-based one for enforcement purposes.

B. Exploiting Enhanced Maps for Road User Charging

Most Geographical Information Systems (GIS) represent roads with one or two polylines depending whether or not lanes with opposite driving directions are physically separated, being these polylines series of nodes and shape points, connected by segments.

Apart from the global inaccuracy (from 5 m in urban areas up to 20 m in intercity roads) and the inaccuracies consequence of the local approximation of the road by series of linear segments, standard maps lack in contents. All these factors limit significantly the benefits of map-aided location for RUC.

The concept of enhanced maps (Emaps) was introduced with the objectives of reaching decimeter accuracy both globally and locally, respecting the shape of the road, and representing all the lanes of the carriageway and their topological links. Our group collaborated with the Geolocalization research team of the Laboratoire Central des Ponts et Chaussées of Nantes, France, in the creation of a novel Emap introduced in the frame of the European Cooperative Vehicle Infrastructure Systems (CVIS) project [13]. This work proved to be useful for enhanced positioning and map-matching at the lane level [20]. It is the authors' opinion that the benefits of Emaps can be exploited for RUC in the scenarios where standard maps fail.

Fig. 4 shows a stretch of one test carried out for a demonstration of the CVIS project. In the upper image the lanes are plotted from the data stored in the Emap. The high accuracy of the lanes allows one to distinguish at the first sight the drift in the position estimate that was caused by the simulation of GPS outage. The map building process, based on kinematic GPS integrated with inertial sensors and off-line processing, assured an error lower than 5 cm with respect to the driven middle-lane. Therefore, it can be claimed that the vehicle is actually on a lane if the confidence on the positioning is high enough. Blue dots represent the assumed true trajectory given by DGPS during a test. Middle and bottom images are to present the benefits of the confidence indicators, to be explained in next section.

C. Integrity Provision

Independently of the charging scheme applicable for a road stretch or area, toll chargers need to know the level of reliability on the charge. For continuous schemes based on cumulative distance, this level can be represented by error-free positioning estimates, such as the one presented in [4]. However, as it has been previously stated, continuous charging schemes are likely to be completed with discrete ones, bringing the need of map-matching. It is the authors' opinion that when map-matching is needed for making the decision of whether or not a user should be charged, a single integrity indicator of the positioning error is not enough to represent the situation.

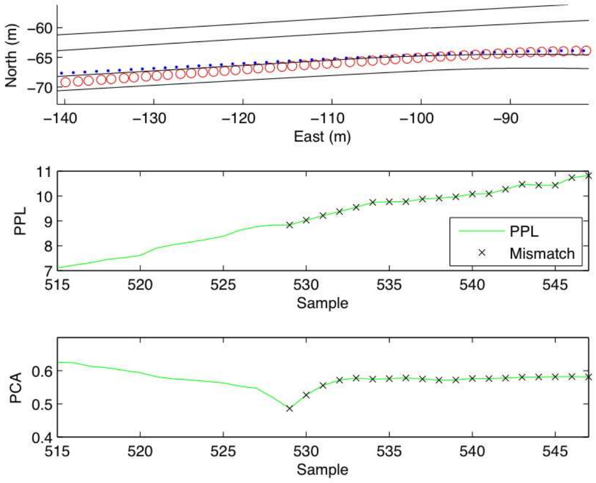

Fig. 4. (Top) Stretch of the trajectory during a period when the position estimates drifted as a consequence of a simulated GPS outage: solid black lines are the map; blue dots are the assumed true positions given by DGPS; red circles are the position estimates given by the PF. (Middle) PPL values during the period when the GNSS coverage is gone. The period of lane mismatch has been marked manually with black crosses. (Bottom) PCA during the same period.

In the frame of the CVIS project, a double integrity indicator that represents the reliability of an algorithm for positioning and map-matching at the lane level was proposed by Toledo *et al.* [14]. We believe that this paradigm can be exploited for road user charging purposes. To do it so, the proposed integrity parameters should represent the confidence on the positioning itself, as well as the confidence on the assignation of a position (or trajectory) to a road segment. The combination of both indexes may offer a representative idea of the positioning and map-matching process because they complement one another. The interest of the confidence on the position for continuous charging schemes is clear and it was discussed before. Nevertheless, there may be cases when the confidence on the position estimates is low due to bad GNSS coverage, but the map-matching problem is trivial, and the final confidence on the assignment can be high. On the contrary, even with a high confidence on the position estimates, if map-matching is difficult in a concrete scenario, the overall confidence should probably be low. In [14] our paradigm of a double integrity index was proven to detect a significant number of wrong assignments at the lane level, improving the overall perception of the vehicle location. This can be exploited for road user charging purposes. The readers are welcome to follow this reference for further details.

The advantages of using these integrity indicators for the distinction of two adjacent lanes of the same carriageway is shown in Fig. 4. This situation could represent the RUC scenario of having contiguous lanes of a highway subject to different charges or the common case of two roads with different tariffs that go parallel and close along a certain distance. As it can be seen in the upper image of the figure, at one point of the trajectory the position estimates drift as a consequence of a simulated GPS gap (in this test the vehicle moves from the left to the right side of the image). The aiding sensor-set keeps the position estimates in good track for a while, but due to its low cost, eventually drifts and locates the vehicle in the contiguous lane. The increasing lack of confidence on the position is represented by the Positioning Protection Level (PPL) value and visible in the middle image of Fig. 4. PPL represents here a protection level based on the covariance of the positioning variables of the filter. However, even with lack of GPS coverage, the positioning and map-matching algorithm would not have allocated the vehicle in the wrong lane if both lanes would not be topologically connected: i.e., if due to physical or legal constraints the vehicle could not make a lane change to the left at that point. This is because the topological information stored in the Emap binds the vehicle location to the areas of feasible maneuvers. In that case, PPL values would still be high and the confidence on the position low, even though the vehicle is correctly assigned to the lane. The use of the Probability of Correct Allocation (PCA) indicator provides the information needed to distinguish between these two scenarios and deciding whether or not the vehicle can be charged. At the bottom of Fig. 4 it can be seen how PCA values become lower and lower, reaching the lowest value when the lane mismatch begins (the PCA value confirms the mismatch). Therefore, PCA enables the decision making of whether or not a rise of the PPL value corresponds to an incorrect lane allocation.

VII. CONCLUSIONS AND FUTURE WORKS

For today, it seems really difficult that any solution exclusively based on GNSS can ensure the high standards for charging reliability of positioning systems for road user charging. For this reason, it is the authors' opinion that GNSS technology must be supported by aiding information coming from onboard sensors and maps. The need of maps appears the most relevant for discrete and mixed charging schemes. In spite of the potential amelioration of the system performance, these complex integrated systems with multiple sources of information present several complications. Among them, two must be underlined: current indicators for positioning integrity, crucial for maintaining the charging integrity, are not prepared for representing an integrated multi-sensor positioning solution and the map-matching process; available digital maps sometimes do not meet the necessary requirements of accuracy and completeness. We have analyzed these issues and suggested recommendations. Several proposals are presented to deal with these drawbacks. Further details of some algorithms presented in the paper could not be given due to lack of space. Interested readers are welcome to follow the corresponding references.

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