Location Privacy Protection for Network-RTK VRS Positioning Users via Mobile Networks

Ruoting Xiong[a], Yi Ren[a], Xin Shi[b], Wei Ren[c], and Gerard Parr[a]

[a]School of Computing Sciences, University of East Anglia, Norwich, UK
[b]CHC Tech Limited, Norwich, UK
[c]School of Computer Sciences, China University of Geosciences (Wuhan), Wuhan, China

***Abstract*—Real-time kinematic (RTK) positioning is a widely used technique that improves positioning accuracy to the centimeter level. In RTK systems, users can utilize the correction data provided by a reference station (RS) to offset their location errors. However, due to the limited deployment and high cost of RS, some places are not covered by physical RS (within 30 kilometers). Therefore, a virtual reference station (VRS) RTK service is provided, where a server generates VRS for users and provides seamless cloud-based network RTK corrections without the need of a real RS. Despite the benefits of VRS services, it poses a risk to user location privacy, as users need to continuously report their standalone calculated positions to the server to obtain the service. In this paper, we propose a privacy-preserving approach for VRS services by multicasting correction data over mobile networks, where joined users can receive valid correction data from the base station in either inactive or connected mode. Experiment results show that the network delay is less than 40ms, throughput is about 16kbps, and the RTK positioning error is 4cm. Other qualitative analyses (such as service continuity and stability) also prove the feasibility and effectiveness of the proposed method.**

***Index Terms*—Real-time kinematic positioning, virtual reference station, location privacy, cellular network, multicast service, correction data dissemination.**

I. Introduction

Many devices like unmanned vehicles and drones have built-in or additional global navigation satellite system (GNSS) receivers, which provide location accuracy of about 10m. This precision can be greatly improved to centimeter-level using the correction data from a nearby reference station (RS). This technique is known as real-time kinematic (RTK) positioning [1]. However, RTK RSs are costly and not widely deployed, leading to incomplete coverage. To overcome this limitation, network RTK (NRTK) technology was developed, with virtual reference station (VRS) being the most widely used method [2]. The basic idea of VRS is to create a fake RS nearby and computes corresponding correction data for each user. Specifically, VRS server selects at least three real RSs near the user to obtain their observations, and calculates the correction data by interpolation or extrapolation methods.

However, VRS positioning poses threats to user location privacy, as users need to continuously report their locations to the VRS server, and the current location must be continuously transferred to maintain accuracy [3]. We assume that the VRS server is interested in inferring more information about the user from the collected locations via artificial intelligence (AI) tools [4]. For example, it may track the user's precise location to know the user's daily routes, and the places they frequently visit. Also, it can identify the user device types based on their locations and speeds, like vehicles, ships and drones. Lastly, it can infer the job types combined with locations and maps, such as fall harvest and fishing.

Another disadvantage of traditional VRS services is their low transmission efficiency. Currently, several companies offer VRS services via subscription, unicasting correction data to the user over mobile networks [5]. Nevertheless, the effective range of VRS correction data is 30 kilometers, and all users within this area may share one copy of the data at service level, resulting in transmission inefficiencies. Furthermore, two-way communication is required for users to provide VRS server with their approximate location information in the national maritime electronics association (NMEA) format.

In this paper, we protect user location privacy in the VRS services by multicasting correction data over mobile networks. The mobile network operator (MNO) requests the VRS server to generate correction data for a specified MBMS area, which is then multicast by all base stations (BS) within that area. The authenticated users do not need to report their locations to the VRS server, but to receive correction data seamlessly while connected to any BS in the area.

II. Related Work

As the demand for high-precision positioning services continues to rise in the low-altitude airspace economy and autonomous driving sectors, RTK services have officially entered the consumer market. There have been many works on the RTK correction data dissemination and VRS services [6], [7].

In Ref. [8], the authors used MQTT to replace the NTRIP protocol, as the server can free from the scale of users. Nevertheless, the users still need expose their geographic locations to get service. The authors in Ref. [9] proposed to use TV broadcast to send correction data generated by FKP method, as broadcasting can improve the transmission efficiency. However, the security of correction data is not guaranteed. The authors in Ref. [10] test the performance of using GEO satellites to send correction data. Jepsen et al. [11] proposed using the LTE positioning protocol (LPP) to transmit

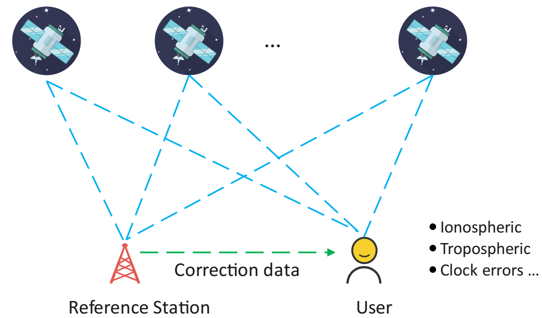


Fig. 1. The RTK system.

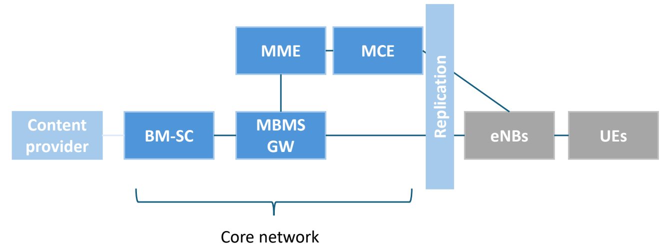


Fig. 2. eMBMS network architecture.

the RTK correction data for drones. LPP operates on a request-response mechanism, where clients request periodic RTK corrections and the server responds with confirmation and the corresponding data. However, this approach is not efficient due to its reliance on unicast transmission. It also incurs frequent signaling overhead, especially during cell handovers and service termination requests. In maritime communication system, VDES [12] is used to send corrections to shipboard positioning module. However, it only supports a maximum transmission rate of 650 bytes/s, and has to reduce size of NRTK correction data.

III. Preliminaries

A. Real-time Kinematic Positioning

As shown in Fig. 1, an RTK system consists of a RS, users, and a communication link for transmitting correction data *(in green)*. This enables users to correct errors such as ionospheric, tropospheric delays, and clock errors [13]. Both the RS and the users receive carrier phase signals from satellites *(in blue)*.

RTK positioning relies on carrier phase measurements and involves several key steps: satellite observation, double differencing, and integer ambiguity resolution. The LAMBDA method is used to convert the floating-point ambiguities into their integer values. Once these ambiguities are successfully fixed, centimeter-level positioning accuracy can be achieved. Users can achieve different levels of positioning precision, i.e. RTK_FIXED, RTK_FLOAT. When RTK_FIXED is displayed, the position error are usually within 10 cm. However, the classic RTK technique relies on a nearby physical RS, and the error grows with the baseline length.

B. Virtual Reference Station Service

VRS is one of NRTK technologies [14]. It is based on having a network of RTK RSs continuously report their observations to a control center (VRS server). These observations are used to create a fake RS, situated only a few meters from the requesting user, and compute the corresponding correction data. The user interprets and uses the data just as if it has come from real RS [15]. The VRS steps are as follows:

1) The observations of κ RSs $\Phi^{(r_1)}$, $\Phi^{(r_2)}$, ..., $\Phi^{(r_\kappa)}$ flow back to the VRS server via Ethernet, Wi-Fi, or radio links.

2) User reports the standalone calculated location ($x^{(u)'}$, $y^{(u)'}$, $z^{(u)'}$) to server in format of NMEA. VRS position is created as ($x^{(v)}$, $y^{(v)}$, $z^{(v)}$).

3) The VRS server generates $\Psi^{(v)}$ as correction data for the user in format of radio technical commission for maritime services (RTCM), typically with a size of less than 2KB.

4) User gets the data via various method such as TCP, UDP protocols, and network transport of RTCM via Internet protocol (NTRIP), and perform RTK positioning.

VRS service does not require the establishment of real RS, extending RTK services beyond the coverage of actual RS networks. Also, it provides monitoring integrity and eliminates the dependence on single RS.

C. Multicast Service in Mobile Network

Take 4G as example, it provides enhanced MBMS (eMBMS) to users, where a eNodeB (eNB) can transmit the same data (identical data) to multiple users simultaneously [16]. For implementing eMBMS, a couple of components are added in the CN. Namely, multi-cell/multicast coordination entity (MCE) and MBMS gateway (MBMS-GW), and broadcast-multicast service centre (BM-SC) [17].

As shown in Fig. 2, MCE serves one or more eNBs, allocates radio resources used for MBMS transmissions, and is involved in the signaling of MBMS session control. MBMS-GW is a logical entity, which physically can be integrated into another network element. It broadcasts MBMS packets to the eNBs that are transmitting the broadcast/multicast content, and also controls the MBMS sessions via mobility management entity (MME). The BM-SC handles MBMS specific activities (e.g., authorizing UEs that request MBMS service, managing sessions, and interworking services among different MNOs in roaming scenarios).

IV. Threat Model

We assume that the adversary is honest and curious, who is interested in inferring more information about the user from the collected locations. The adversary here is the VRS service company that owns servers and a network of RTK RSs. These passive adversary may pose the following threats:

- *Tracking Threat:* the adversary can collect GNSS location information of each user continuously. They can learn the user's movement patterns (daily routes), the places they

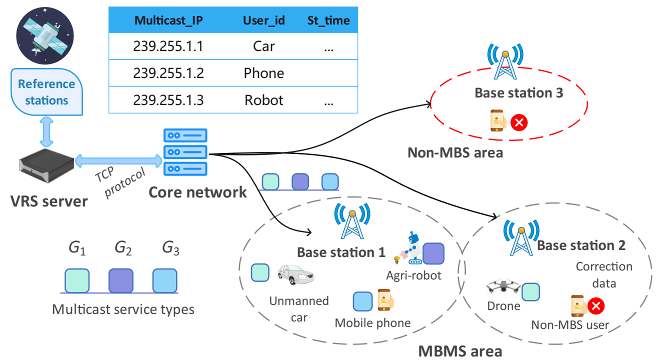


Fig. 3. The network model of the proposed scheme.

frequently visit (home, workplace, and hospital), and even predict their future locations.

- *Device Identification Threat:* the adversary can identify user device types based on their locations and speeds. They may infer whether it is a stationary object or a high-speed moving object. Combined with the terrain on the map, the device type can be identified, such as cars (on the street, high speed), ships (near the ocean or port, middle speed), and drones (at low altitude, low speed).
- *Task Inference Threat:* the adversary can infer the type of work you do. For example, when the users are located in rural area (such as a farm) over a long period, the adversary may know that the task is for fall harvest. Similarly, if users visit the coastline periodically, the job type could be ocean freight. In urban city, the adversary can also easily know the applications you use for RTK positioning, like autonomous driving, mapping and surveying.

V. Network Model

In this section, we show how user location privacy can be protected by enabling multicast service in mobile networks. The main idea is to first compute correction data $\Psi^{(v)}$ for a given service area, and then have all BS within the group multicast this data to users. Given that the propagation range of BSs is approximately 3 kilometers, we can guarantee that the correction data received by users remains valid within the coverage. Our design follows the 3GPP technical standard (TS) 38.305 [18].

Fig. 3 shows the network model. It consists of the VRS server, the CN, BSs and mobile terminals. We assume that different types of BSs are deployed in an area, and there are multiple types of users requiring RTK services. The CN can host IP address for different multicast service, such as high (pink), mid (green) and low (blue) RTK frequency services. Within the MBMS area, each BS multicasts the correction data to the users. Authorized users can receive the data in either idle or connected mode, while unauthorized users are unable to decrypt the multicast data.

As shown, the network model consists of the VRS server, the CN, BSs and mobile terminals.

- VRS server: As a content provider, VRS server monitors the integrity of RS data, and provide the correction data for network operators through various methods such as TCP, UDP, NTRIP protocols.
- CN: It defines the service area and provides the multicast service to users, including the access control, share key distribution and content delivery. It loads the correction data from the VRS server, and sends it to the serving BSs.
- BS: The BSs are signal transmitters, and they send the corrections over radio links. All BSs support the handover mechanism. Usually, 4G BS has about 3km range, while that of 5G has 2km range.
- Mobile terminals: There are users like self-driving cars, agricultural robots, delivery drones and other equipment. They can do GNSS positioning independently. After they join the multicast group, they can receive the correction data for RTK positioning.

A. Workflow

Our proposed scheme mainly consists of three steps, namely VRS calculation, multicast service and RTK positioning.

1) Step 1 (VRS Calculation): The CN offers the location information of BSs within the MBMS area, and the VRS server computes the corresponding correction data for this group. For public networks, the location information of deployed BSs is transparent and available online. For private networks, the locations of BSs are not public and may be mobile, but they can easily request correction data at their current locations.

2) Step 2 (Multicast Service): The CN starts the multicast service, and users request to join the multicast group. The CN distributes the same shared keys within the same group. Then, the BSs multicast the correction data to authenticated users, and only the users in the group can decrypt the data.

Specially, we use srsRAN [19], an open-source 4G software radio suites, to set up a private 4G testbed with eMBMS, where we use UDP protocol to transmit multicast data over 4G. The size of correction data is small, usually less than 2KB, which can be encapsulated well by UDP protocol. The traffic is transmitted through the “sgi_mb" interface from 4G eNB side using an IP range of 239.255.1.*, and is then disseminated to users in a multicast mode by wireless link over the air. After joining the multicast group, the users can receive the correction data through the “tun_ue" interface.

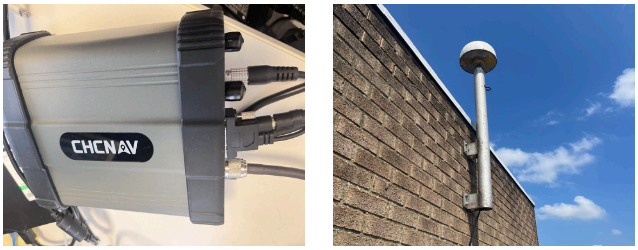
3) Step 3 (RTK Positioning): Receiving correction data via multicast, users equipped with RTK chips can refine their satellite-based positioning. When they move to the next location, this process is repeated.

VI. Performance Evaluation

In this section, we introduce the experiment setup and system performance.

A. Experimental setup

In this experiment, we configure two USRP B210s, each connected to an HP i5-10500 CPU@3.10GHz x86 computer



(a) RTK reference station (b) Antenna

Fig. 4. The RTK reference stations used in system.

with 16 RAM running Ubuntu22 using USB cables. Specially, one computer is set to run eMBMS, 4G CN and eNB, and the other one simulates the user side. The network is configured with a subcarrier spacing of 15 kHz, and bandwidth is 10MHz. We use two Python scripts with the socket library to run UDP and TCP protocols (one for the user side and one for the server side). At the user side, the multicast traffic from UDP is forwarded to TCP localhost: 2000. The tools such as wireshark, ping, etc. are used to measure network performance.

We use the ublox ZED-F9P module as the RTK chip with an update frequency of 1Hz. We run a submodule called "rtknavi" in the RTKlib2.4.3 software, and use *wine* to enable Windows executable on Ubuntu for real-time RTK positioning. Within RTKlib, we configure the input streams as serial (Rover) and TCP client (Base station), and then save the RTK positioning results to a log file in time sequence.

The correction data is provided by CHCNAV [20] in the format of RTCM. We fetch the data from their server through TCP protocol. The RTK RS used are shown in Fig. 4, where Fig. 4(a) shows the advanced GNSS RS P5, and Fig. 4(b) shows the antenna mounted on the roof with clear sky. The P5 RS can receive and process the signals from all current GNSS constellations (GPS, GLONASS, Galileo, BDS).

B. System performance

1) Throughput: We measure the network throughput in the multicast mode on the user side. Fig. 5 shows the transmission of data in bits per second (bps) over time.

The figure shows that there are two distinct levels of data rates: one level is around 15,000 to 17,500 bps. The other level is around 7,500 to 10,000 bps (observation data). Both data streams maintain relatively stable rates over time, suggesting a consistent transmission of correction data.

2) Latency: We measure network latency for uplink and downlink over a 100-second period, during which the user and server ping each other via the radio link.

Fig. 6 presents the histogram of network latency. For uplink transmission, all network latency is within 38.4ms, and the smallest latency is 17.6ms. The most happened in uplink network latency is in range 20-25ms, and fewer is less 20ms. While for downlink situation, the smallest is 17.4ms, and maximum is 37.5ms. Most latency falls into 25-30 group, fewer is in range of 35-40ms. Overall, the average network latency of uplink transmission is 28ms and that of downlink is 27.5ms.

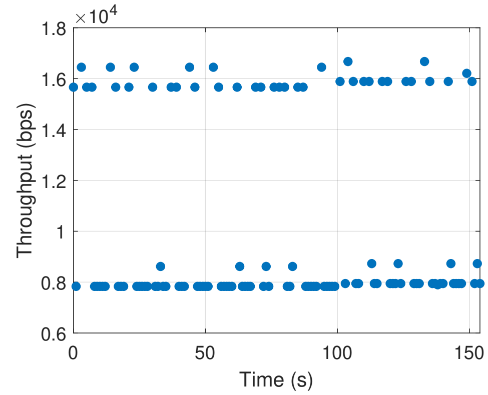


Fig. 5. System throughput over time.

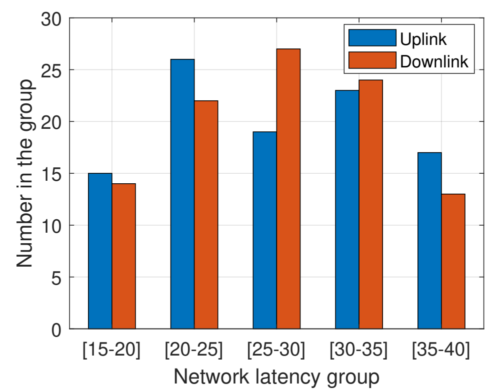


Fig. 6. Histogram of network latency.

Other network metrics like reference signal received power (RSRP) is about -96dB on average, and signal-to-noise ratio (SNR) is 12.

3) CPU consumptions: We measured the CPU consumption when running different programs, with the server-side CN consuming 1.7%, the eNB consuming 23.8%, and the eMBMS consuming only 2.7%. On the user side, the CPU usage of the eMBMS service was 12.1%.

4) Positioning error: We evaluate both GNSS and RTK positioning error when users are static in terms of standard deviations in north (sdn), east (sde) and up (sdu). Fig. 7 shows the average positioning error (m) in sdn, sde and sdu with the confidence interval (95%) as error bar. Regarding GNSS measurements without RTCM data, the positioning accuracy can only achieve meter level. The average results of sdn, sde and sdu are 4.23m, 3.59m and 8.4m, respectively. Their confidence levels are 0.0317, 0.0276, and 0.0405.

For RTK positioning, records of sdn, sde and sdu are only collected when the RTK_FIXED solution is displayed.

We can see that the average RTK positioning errors for sdn, sde and sdu are approximately 0.03m, 0.02m and 0.06m, respectively. Their confidence levels are 0.0026, 0.0012 and 0.0064. According to the log file, the minimum errors of sdn, sde and sdu are 0.01m, 0.007m and 0.019m, while the

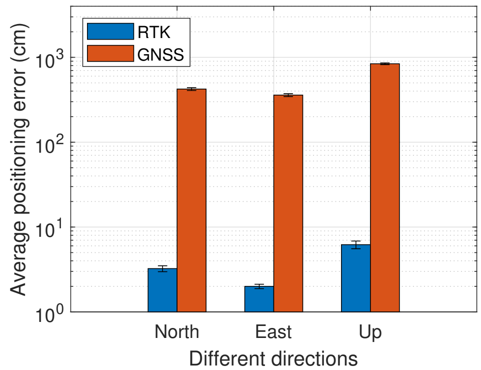


Fig. 7. Average positioning error in sdn, sde and sdu with confidence interval.

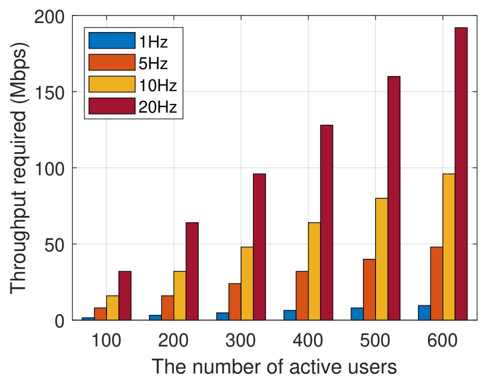


Fig. 8. Throughput required for traditional VRS service under single 4G base station.

maximum errors are 0.68m, 0.35m and 1.76m. To conclude, users can perform precise RTK positioning with error less than 4cm after receiving correction data from the multicast service.

5) Single-base station throughput of traditional VRS service and ours: We qualitatively illustrate the throughput required for single 4G/5G BS under varying numbers of active users and VRS update frequencies. We set the maximum number of active users for a 4G BS is 600, and that of 5G is 1000. We set the size of RTK correction data is 2KB. The update frequency of VRS messages depends on the specifications of the RTK chip. The minimum frequency is 1Hz, with possible configurations including 5Hz, 10Hz, and up to 20Hz (i.e., 20 updates per second) [21].

As shown in Fig. 8, the traditional VRS service will cause communication pressure on 4G BS. When the number of active users reaches 500 to 600 and the VRS update frequency is 20Hz, the throughputs required are 160Mbps and 192Mbps, respectively. However, 4G can only theoretically support 150Mbps. As the frequency of updates and the number of users increase, the unicast system's required throughput rises accordingly. When the update frequency is below 10Hz, no throughput overflow occurs under different numbers of active users. However, it still poses a potential threat to future real-time location services, especially as user connections become denser.

Similar in 5G, it will cause the throughput explosion when

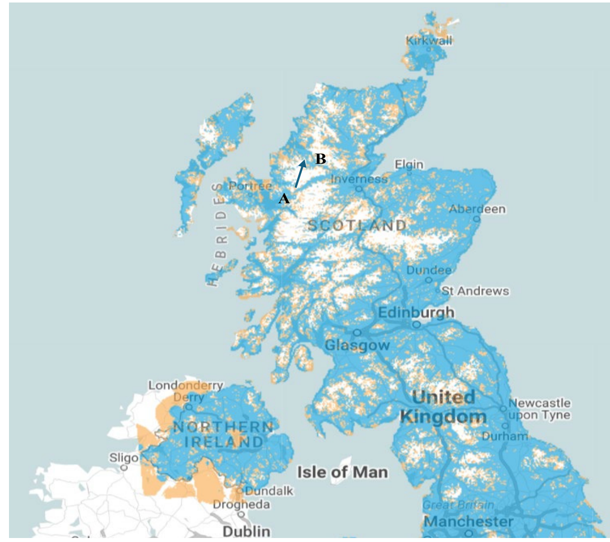


Fig. 9. Network coverage map in UK (Take O_2 as example).

the number of users reaches 800 and 1000. When setting the update frequency as 20Hz, the throughput required are 256Mbps and 320Mbps. Although it may not cause any throughput traffic issues for 5G BS as it supports data rates up to 1Gbps, the coverage of 5G BSs needs to be considered.

The required throughput for our scheme remains constant as the number of users increases, with values of 0.016, 0.08, 0.16, and 0.32 Mbps, respectively. The maximum throughput is below 4 kbps, occupying a minimal communication bandwidth. Additionally, since our scheme delivers corrections in a multicast manner, it can theoretically support an unlimited number of users.

C. Service continuity and stability

Our scheme can maintain RTK service stability and continuity regardless of the user mobility.

1) Service continuity: If users move to a place without network coverage, they can use the correction data previously received from the 4G/5G BS for RTK positioning, as its effective range is 30km. After reconnecting to the network, they can update their correction data. Fig. 9 shows the network coverage map of O_2 in UK (including 2G-5G) [22].

As shown in Fig. 9, there are some places without signal coverage of public networks, such as urban areas, mountains, and islands. We found that the coverage areas of other different MNOs is similar, and forests and ports are not included [23]. Consider a scenario where users travel from A to B on the map, where the distance is within 30km. Once users lose connection to the BS, the transmission of VRS correction data becomes impossible. For NRTK methods, the previously received correction data quickly loses validity within a few seconds. In contrast, the PPP-RTK method allows users to maintain RTK positioning throughout their journey, ensuring that the old correction data remains usable until they reach point B thereby guaranteeing service continuity. The correction data used in NRTK is known as observation space representation, while PPP-RTK relies on state space representation. Since the network architecture for transmitting correction data remains unchanged, with only the content differing, a detailed comparison of these two methods is beyond the scope of this discussion. In urban areas, network coverage is already extensive, with BSs typically spaced no more than 30 kilometers apart. In the future, the coverage gap in urban networks is expected to narrow further. Therefore, the VRS service continuity of our method is guaranteed.

2) Service stability: When users move within the MBMS coverage area, key updates are not triggered, as handover events do not occur during transitions between the serving and target base stations. Instead, users perform only cell reselection. During MSK updates, the key distribution latency ranges from 100 to 500 ms. For 1Hz and 5Hz RTK chips, this time will not influence the correction data receiving. For 10Hz RTK chips, handover time less than 100ms is required. For 20Hz chips, handover time of 50ms is required. Although a longer MSK update interval may slightly reduce the frequency of data reception, the impact is minimal. Therefore, our scheme can ensure the VRS service stability regardless of user's mobility.

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VII. Conclusion and Future Work

This paper exploits the existing multicast services in cellular networks to securely disseminate VRS correction data. Experimental results show that the proposed scheme is feasible in terms of throughput and positioning error. In addition, our scheme can provide continuous and stable services regardless of the user's mobility. In areas without signals, setting up a private network with VRS services is a fast and simple deployment. Future work will focus on expanding the service range and testing the performance when users are moving.

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