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GNSS Augmentation by FM Radio Symbiosis

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ABSTRACT Emerging applications, such as improved all-weather safety for self-driving vehicles, require public positioning precision and reliability beyond the capability of open global navigation satellite system (GNSS) services. To meet these requirements, next-generation public positioning, navigation, and time (PNT) services should: 1) deliver ubiquitously available differential corrections and assistance information for massive numbers of concurrent users with fixed delay, indoor penetration and stable bit rate signals and 2) have navigation signals that are extremely enriched against challenging scenarios. The dilemma is that the free-of-charge public PNT service makes it a formidable challenge to build a dedicated information infrastructure. In this context, a natural question arises: where should we seek next-generation public PNT services in the age of Internet of Things? In this paper, we propose GNSS augmentation by FM radio symbiosis. Specifically, we propose GNSS augmentation-optimized digital data broadcasting for which the signal symbiotically co-exists with the analog FM radio in band and in channel without sensibly affecting the existing FM service. With this symbiotic digital data broadcasting, we then propose a GNSS augmentation system that can: 1) broadcast real-time kinematics correction to massive numbers of concurrent GNSS receivers to achieve outdoor precision at the centimeter-level; 2) deliver fine time GNSS assistance for significantly improved receiver sensitivity; and 3) provide common-view timing to enable GNSS independent ground positioning beacon signals. A prime challenge therein is to separate the symbiotic digital signal from the much stronger, spectrum-overlapping co-channel FM signal; this challenge represents a non-orthogonal de-multiplexing problem that is solved by a novel modulation structure. A prototype was designed, and field tests by authorized third parties were conducted with excellent results.

INDEX TERMS GNSS augmentation, FM radio, PNT, RTK.

I. INTRODUCTION

Position and time are prime elements in future networks that interconnect human, intelligent artifacts and nodes of Internet of Things. Nowadays, people mainly rely on the global navigation satellite system to obtain position, navigation and time (PNT) service. It has a proven positioning precision from several to tens of meters, which satisfies the precision requirements of most of daily applications.

Nevertheless, in recent years, there are more and more emerging applications, such as self-driving vehicles [1], [2], unmanned air vehicle (UAV) surveying [3], fine management of public-renting bicycles, which requires a much higher positioning precision and reliability than ever, obviously beyond the capability of open GNSS services. For example, precise and reliable positioning is prime to self-driving vehicles. Intuitively, a self-driving vehicle learns about its surroundings by real time observations from various sensors, and then makes a decision by fusing these observations and knowledge retrieved from either local or network database with the location from GNSS system as an important reference input. The more precise and reliable the location is, the easier and quicker for a self-driving vehicle to make an optimal decision [4].

The precision limitation of GNSS open services originates from its broadcast ephemeris error, inter-satellite clock synchronization error and signal propagation path modeling error. The reliability limitation is mostly incurred by its weak ground signal that is vulnerable to shading, interference and spoof, since the GNSS satellites transmit navigation signal from twenty thousand kilometers away in space. Under such a circumstance, augmentation is the common way to improve GNSS performance. An ideal navigation augmentation system for public PNT services, as required by self-driving vehicles, should:

- Not change the way of people using current daily GNSS services, and its signal should be ubiquitously available, free of charge and unidirectional.
- Deliver real time RTK differential correction for centimeter level outdoor positioning and fine time GNSS aiding for improved indoor sensitivity to unlimited number of simultaneous users [5].
- Provide extremely enriched reference signals to survive harsh context such as ambient fading, strong interference and intentional spoofing.
- Possess sufficient bandwidth to broadcast update of maps and roads emergency warning and even timeout of traffic lights.

II. EXISTING GNSS AUGMENTATION SYSTEMS

Generally, a GNSS augmentation system helps reduce the positioning error of a receiver by communicating to the receiver with real-time differential corrections, shortens the time to first fix, and improves the receiver sensitivity by providing information assistance. The system also provides original navigation message, a reference time and even additional measurements for receivers to combat ambient shading and hostile spoofing. Augmentation systems can be either space-based or ground-based.

Space-based augmentation systems (SBAS) usually employ L-band GEO satellites to broadcast augmentation information [6], such as WAAS (wide area augmentation system) in U.S., EGNOS (European geostationary navigation overlay service) in Europe, GAGAN (GPS-aided GEO augmented navigation) in India and QZSS (quasi-zenith satellite system) in Japan. These systems are able to improve precision to several meters and broadcast GNSS integrity warnings, which are rather important in applications such as civil aviation. Recently, low earth orbit (LEO) communication satellite networks have also adopted GNSS augmentation. Compared to GEO satellites, LEO communication satellites have much stronger ground signal power; moreover, the rapid relative movement of ground users and LEO satellites can provide a Doppler-based backup positioning capability. The advantage of SBAS is global coverage; the drawbacks of SBAS are the limited indoor availability and the relatively high cost in terms of user receivers.

In contrast to SBAS, ground based augmentation systems feature low costs and ease of deployment, for private or public use. With the development of public land mobile communication and proliferation of the mobile Internet, GNSS augmentation by a cloud computing system over mobile Internet has become prevalent. A-GNSS is currently the most widely used GNSS augmentation over the mobile Internet [7]. A standalone GNSS receiver must decode orbital information of the satellites from the GNSS signal to calculate its own position, which often takes 30 seconds on average. In A-GNSS, the network operator deploys an A-GNSS server to cache such GNSS data for an A-GNSS-capable device to download over mobile network radio bearers, such as 3G/4G. Usually, as the data rate of these bearers is relatively high, downloading orbital information takes much less time.

A-GNSS also provides GNSS navigation message and time estimates, which are helpful in signal acquisition. If the time estimate error is less than 1 ms, then the code phase search space can be shortened; such an A-GNSS is called a fine time A-GNSS. Otherwise, all possible code phases should be searched; such an A-GNSS is called a coarse time A-GNSS. Therefore, A-GNSS can significantly improve the startup performance of a GNSS receiver, not only the time to first fix but also the sensitivity. In addition to A-GNSS, an allied technology is high-sensitivity GNSS. Compared with A-GNSS, high-sensitivity GNSS cannot instantaneously provide a fix when the GPS receiver has been off for some time. Another typical approach of GNSS augmentation by cloud computing over mobile Internet is network RTK service. It involves modernized outdoor differential positioning with centimeter-level precision. In network RTK, a rover receiver reports its approximate position to the CORS server, and then, the server generates virtual RTK correction data that best fit the rover receiver and delivers the data to the rover receiver. If the communication link between the server and the rover receiver is ideal, then the rover receiver can always have the best available RTK correction data for precise positioning. The aforementioned cloud computing over mobile Internet is built upon best effort services but not a guaranteed services model, i.e., the maximum concurrent rover receivers are limited by the servers that the cloud can support. In such a case, the network RTK is applicable in scenarios that have low duty cycle, low sensitivity on service delay and low concurrency. Such scenarios include surveying, deformation monitoring, and intermittent tracking of property. However, future high-precision public PNT services need to support massive numbers of concurrent users, such as self-driving vehicles, with long on-line time and sensitivity to the age of the RTK correction data.

Broadcasting is the most efficient method to serve applications that have massive numbers of concurrent users. Early public wireless communication systems were broadcast communications systems, such as AM broadcasting, FM broadcasting, satellite and terrestrial TV broadcasting [8]. Over the years, legacy analog broadcast systems have become fully digitalized or are being transformed to digital-analog coexistence. Taking FM for example, Digital audio broadcasting (DAB) and Digital Radio Mondiale (DAM) are full digital audio broadcast standards in Europe, and RDS and HD Radio enable digital-analog coexistence. RDS is a communication protocol for embedding small amounts of digital information on an FM subcarrier. HD Radio is a high-definition digital audio broadcasting method for 400 kHz FM transmitters, such as those in the United States. The idea of HD Radio is that when the spectrum of digital broadcasts is sufficiently separated from that of FM, they will not affect each other. Broadcasting has also become an integral constituent of public land mobile communication systems [9].

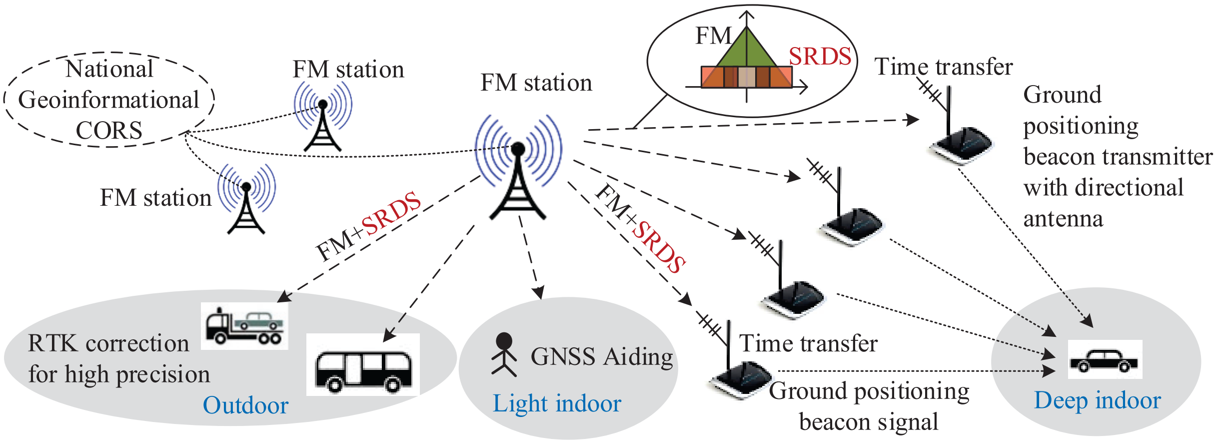


FIGURE 1. **An illustration of the SRDS-enabled GNSS augmentation system.**

Multimedia broadcast multicast service (MBMS) was initially introduced in 3GPP Rel-6, and it evolved to MBSFN in 3GPP Rel-7 and has further evolved to MBMS (eMBMS) since 3GPP Rel-9 [10], [11].

According to a survey of those existing broadcast technologies, attention is increasingly being paid to audio and video services with enhanced definitions, whereas there is a lack of a wide area broadcasting technology that has a lower data rate but is suited for applications such as public GNSS augmentation. Here, we will introduce our proposed FM symbiosis for GNSS Augmentation.

III. FM SYMBIOSIS FOR GNSS AUGMENTATION

As FM is the most widely adopted and infrastructural well-built broadcast system worldwide, finding a method to reuse the broadcast infrastructure for next-generation PNT service will be a significant advance toward the ideal navigation augmentation system. Such a new method should be optimized to PNT service while requiring a minimum amount of modification to an FM station. Preferably, the new method should require no reduction in FM transmission power and no replacement of FM transmitters and should be compliant with the signal quality requirements of the FM transmitter.

A. ARCHITECTURE

In nature, symbiosis is commonplace. The diversity and the associated functions of symbiosis are crucial for nature's survival. Symbiotic relationships have been defined as the associations of two or more organisms that closely live together. Such partnerships have been driven and favored by one or more benefits improving fitness or yielding selective advantages for at least one of the species involved. Inspired by the symbiosis in nature, we propose an FM radio symbiotic system. In the symbiotic system, a PNT-optimized digital data broadcast signal symbiotically co-exists with the analog FM radio, i.e., its spectrum underlays with the host FM, but it has much lower power without violating the regulation of the FM transmitter [12]. The digital data broadcast signal forms a symbiotic radio data system (SRDS), which has much higher bit rates than existing RDSs based on stereo FM subcarriers.

With such an FM radio symbiosis as the core concept, we propose a GNSS augmentation system, as illustrated in Fig. 1. The system consists of four segments: the national geo-informational Continuously Operating Reference Stations (CORS) network, the SRDS-enabled FM data broadcast network, ground positioning beacon transmitters and the user receivers. The CORS network functions as the RTK correction data producer, and the SRDS-enabled FM broadcast network serves as a distributer broadcasting GNSS assistance and timing information. The users refer to the consumers of all the GNSS augmentation data. The outdoor users often have a clear view of the sky; thus, they can achieve centimeter-level positioning with RTK correction data. The indoor GNSS users can still position themselves by achieving high sensitivity for the receiver with assistance from the SRDS. In some scenarios, such as deep indoors, where both GNSS signals and the SRDS are not available, the ground positioning beacon transmitters provide an alternative PNT service. For time synchronization, these ground positioning beacon transmitters receive the SRDS signal using a directional antenna to combat multipath fading and noise. All the users, if the SRDS is available, can detect GNSS spoofing via the real-time navigation message and timing information provided by the SRDS.

B. A PROPOSED DESIGN OF THE SRDS

We propose an exemplar design of the SRDS here. As a data broadcast system, the proposed SRDS has consecutive superframes in the time domain. Each superframe consists of a fixed number of frames, as shown in Fig. 2. To support GNSS assistance, the first frame of each superframe is a control channel, which has the universal time coordinated (UTC) geo-position of the transmitting FM station. The modulation of the proposed SRDS is Orthogonal Frequency Division Multiplexing (OFDM), which is a most spectrum-efficient modern modulation widely used in systems such as 4G

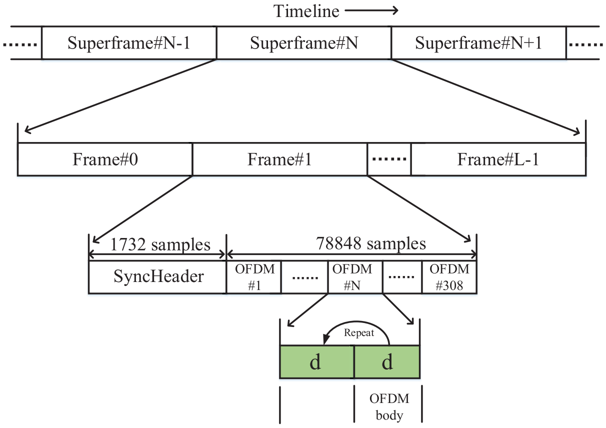


FIGURE 2. **The frame structure of a typical SRDS with a proposed ''1+1'' OFDM modulation structure that allows the receiver to separate the SRDS signal from the much stronger FM signal.**

and WiFi. Each frame consists of a synchronization header and an OFDM symbol with QPSK modulation. To improve the performance under the multipath fading channel, channel coding and frame-based interleaving of different modes are adopted.

C. SEPARATING THE SYMBIONTS

In existing digital broadcast systems, such as HD Radio and CDR, analog FM and digital signals are sufficiently separated from each other, which can be easily achieved by using a filter at the receiver. However, in the SRDS, FM and the SRDS spectrum significantly or even completely overlap. At the receiver side, separating the simulcasting FM signal and the SRDS signal poses a non-orthogonal de-multiplexing problem, which is a new problem in modern digital signal processing. Considering this problem, we propose a modulation structure called the ''1+1'' modulation structure, i.e., an OFDM symbol that has a 100% cyclic prefix, as shown in Fig. 2. This is in contrast with existing OFDM communication systems, all of which attempt to optimize the cyclic prefix to be as short as possible. With such a modulation structure, we propose the following theory to separate the symbionts. Define $F(t)$ to be the FM signal and $D(t)$ to be the SRDS signal; the transmitted hybrid signal can be expressed by $S(t) = F(t) + k \cdot D(t)$, where k is a power factor that determines the FM and SRDS power ratio. If the duration of the OFDM body is T and $t \in [0, T]$, then for an OFDM body, we have $S(t) - S(t + T) = F(t) - F(t + T)$. In other words, when the OFDM body and the prefix are identical, the subtraction removes the OFDM signal, resulting in subtraction of two sections of FM signals with identical amplitude. According to [13] and [14], these two FM signals are analytically separable. After the two sections of FM signals are separated, the original digital OFDM signal can then be recovered. Regarding multipath channels, the procedure becomes more complicated but follows a similar approach.

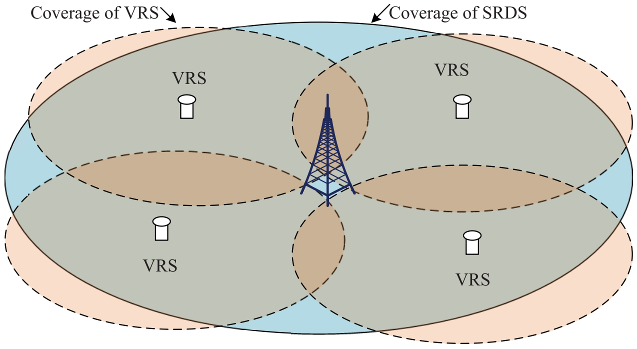


FIGURE 3. **An exmaple brodcast RTK system.**

D. SRDS FOR HIGH POSITIONING PRECISION

The most fundamental application of SRDS for GNSS augmentation is broadcasting RTK correction data. Because the broadcast link is unidirectional, the CORS server does not know the position of any rover receiver. It generates a single or several virtual reference station (VRS) RTK correction data according to the geo-position of the transmitting FM station. We call such an RTK system ''broadcast RTK,'' in contrast to the existing ''network RTK''. Fig. 3 illustrates an example broadcast RTK system that a FM station broadcast 4 VRS correction data. Such a broadcast RTK system has no upper limit on simultaneous rover receivers. In RTK systems, the positioning precision is typically expressed by $E = F + 10^{-6}D$, where E is the final positioning error in meters; F is a fixed value, typically less than 2 cm; and D is the distance from the rover receiver to the reference station, in meters. In a broadcast RTK system, a rover receiver can always select the correction data from the nearest VRS and thus minimize D. Typically, D is less than 60 km, which corresponds to a worst-case positioning precision of approximately one decimeter for the proposed broadcast RTK system.

E. SRDS FOR HIGH SENSITIVITY GNSS

The SRDS is also designed to support high-sensitivity GNSS assistance [15]. The sensitivity of a GNSS receiver is limited by three factors: the demodulation sensitivity of the BPSK-modulated GNSS navigation message, the GNSS signal acquisition sensitivity and the tracking sensitivity. For a standalone GNSS, the navigation message demodulation sensitivity is much lower than the acquisition sensitivity, which is also substantially lower than the tracking sensitivity. If navigation message is obtainable from an aiding system, then the next task for a GNSS receiver is to attempt to improve acquisition sensitivity toward the value of the tracking sensitivity.

Fig. 4 shows the acquisition flow of the SRDS-aided high-sensitivity GNSS receiver. The repeated synchronization headers within the SRDS are used to produce a reference one-pulse-per-second (One PPS) timing, which is further used to estimate the drift of the local oscillator. The One PPS is also combined with the universal timer coordinated (UTC) signal

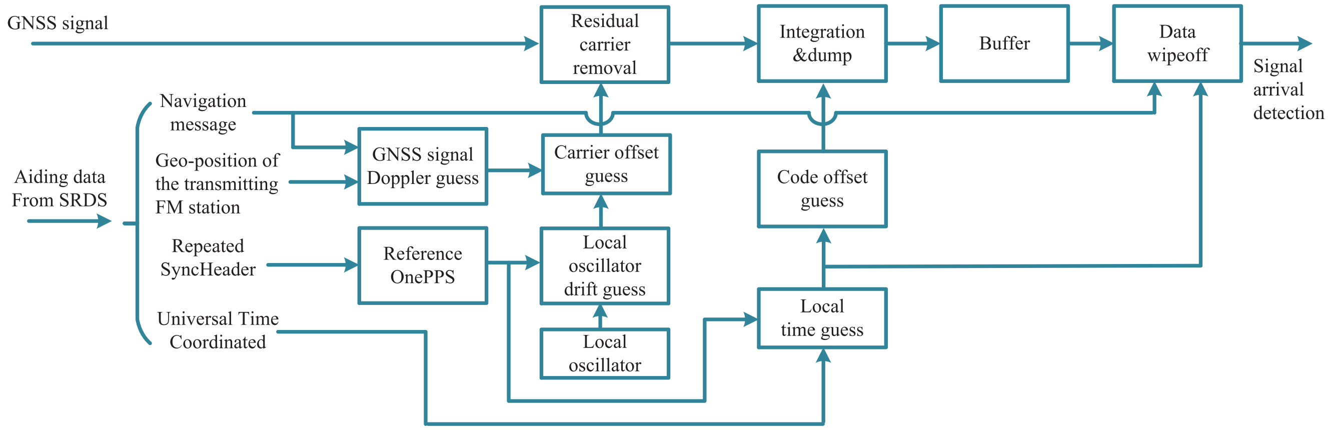


FIGURE 4. **Signal acquisition flow of an SRDS-aided GNSS receiver.**

to obtain the local time estimate. The GNSS signal Doppler at the receiver can be estimated using the transmitting FM station's geo-location, the ephemeris of GNSS satellites and the local time estimate. The local oscillator drift estimate and the GNSS signal Doppler estimate are added together to remove most of the residual carriers, thus significantly reducing the carrier offset search space. Assuming that the maximum coverage of transmitting FM is within 60 km, the estimated local time has a maximum error of 0.2 ms, which reduces the code phase offset search into a 1/5 subspace of the full space. The integration in acquisition process dumps a set of periodic results, which are buffered to await the incoming navigation message from SRDS before performing data wipe-off. After the data wipe-off, the results can be used for signal arrival judgment.

The differences between the proposed SRDS broadcast GNSS assistance and the existing network GNSS assistance over mobile Internet are as follows: (1) the aiding navigation message is continuous in the proposed broadcast assistance, whereas in network assistance, the navigation message is transferred to the user receiver upon request, and the user should always guess what the next data bit will be according to the history in data wipe-off; (2) the broadcast assistance is a fine time assistance, in which local UTC time has a maximum error of 1/5 of the period of a GPS spread code, while most of existing network assistance is coarse time, in which the local UTC time estimate error is higher than the period of a GPS spread code; (3) a receiver with SRDS can obtain a continuous frequency reference from the periodical synchronization header, which is very useful in extending coherent integration time. Those aforementioned differences potentially help an SRDS-aided GNSS receiver achieve better acquisition sensitivity than those aided over the mobile Internet.

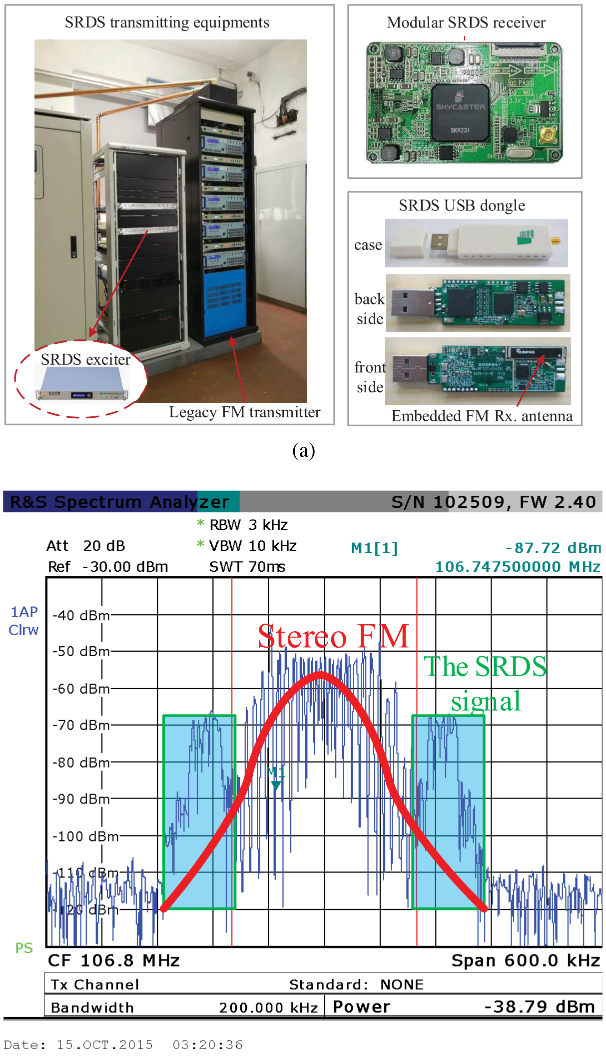
F. SRDS FOR TIME TRANSFER

For scenarios in which GNSS signals are significantly attenuated, such as deep indoors, a ground positioning beacon signal is an important PNT alternative. A ground positioning beacon transmitter must be time synchronized, just as in the synchronization of GNSS space vehicles. In a standalone GNSS timing system, the typical synchronization error is tens of nanoseconds. When the SRDS is available, satellite common-view time transfer is applicable, which is one of the main methods for remote precise time and frequency transfer. In common-view time transfer using SRDS, remote GNSS receivers simultaneously receive a one-way time signal from the same set of GNSS satellites at the same epoch and RTK correction data from the SRDS, and then, they perform common mode cancellation of the timing errors. The accuracy of this method can reach several nanoseconds, which is significantly higher than the standalone GNSS timing.

Although GNSS are dependable most of the time, the possibility of outage exists. In such a case, the time transfer purely based on the SRDS is preferable. The time transfer performance of a wireless link is proportional to the product of the bandwidth and its signal to noise ratio (SNR). The SRDS is a narrow band signal with a bandwidth of less than 300 kHz; thus, SRDS-based time transfer is applicable in situations in which the SNR can be guaranteed. Fortunately, ground positioning beacon transmitters are often installed on the roofs of buildings, where very high SNR is available via the direct path of an FM signal in most cases. Although a directional antenna such as a Yagi antenna is helpful in constraining multipath signals, as shown in Fig. 1, timing transfer solely based on the SRDS poses a super-definition first path time of arrival estimation problem that is worth further investigation.

IV. PROTOTYPING AND PERFORMANCE EVALUATION

For proof of concept, a prototype system was assembled that had past FM compatibility certification and showed very impressive performance in third-party RTK positioning tests.



(a)

(b)

FIGURE 5. **(a) SDRS transmitter-side equipment and the user receivers. (b) Spectral relationship of the FM spectrum and the SRDS spectrum.**

A. THE PROTOTYPE

In the left side of Fig. 5(a), we show a photograph of the designed SRDS exciter and legacy FM transmitter at the transmitter side. The SRDS exciter is based on a software-defined radio (SDR) with the size of a standard 1U chassis. The outputs of the SRDS exciter and FM exciter are then combined by an RF combiner and sent via a legacy FM transmitter. In Fig. 5(b), we show the spectrum of the practically designed SRDS and FM mixed signal. Although the proposed "1+1" modulation structure allows for arbitrary subcarrier allocation, the spectrum of the practically designed SRDS was optimized to penetrate the main lobe of the FM spectrum less. However, the spectra of the two signals are still substantially overlapping to survive existing FM transmitters with 300 kHz typical filter bandwidth in countries such as China.

In Fig. 5(a) right, we show a photograph of a modular SRDS receiver and a SRDS USB dongle, both of which are also based on SDR. The modular receiver is the size of a name card. The SRDS USB dongle is for use with a laptop computer and has the size and shape of a USB flash disk. FM is a meter wave signal, and people are familiar with the commonly used FM telescopic antenna that has a length of 1 m or so. In designing the USB dongle, we used a surface-mounted embedded FM receiving antenna that has a size of only 25mm × 5mm, as shown in the front photo of the USB dongle in the right side of Fig. 5(a).

TABLE 1. **Results of FM compatibility certification test, (a) Recovered sound SNR, (b) Recovered sound distortion.**

Power ratio	Left channel		Right channel	
	RMS*	QPK*	RMS	QPK
-14 dB	64.5 dB	60.3 dB	64.5 dB	60.5 dB
-17 dB	70.4 dB	66.0 dB	70.3 dB	66.0 dB
-20 dB	76.3 dB	72.4 dB	76.3 dB	72.4 dB
-23 dB	81.2 dB	77.4 dB	81.1 dB	77.3 dB
-27 dB	84.8 dB	84.9 dB	84.7 dB	84.9 dB
-30 dB	86.4 dB	83.0 dB	86.5 dB	83.0 dB

(a)

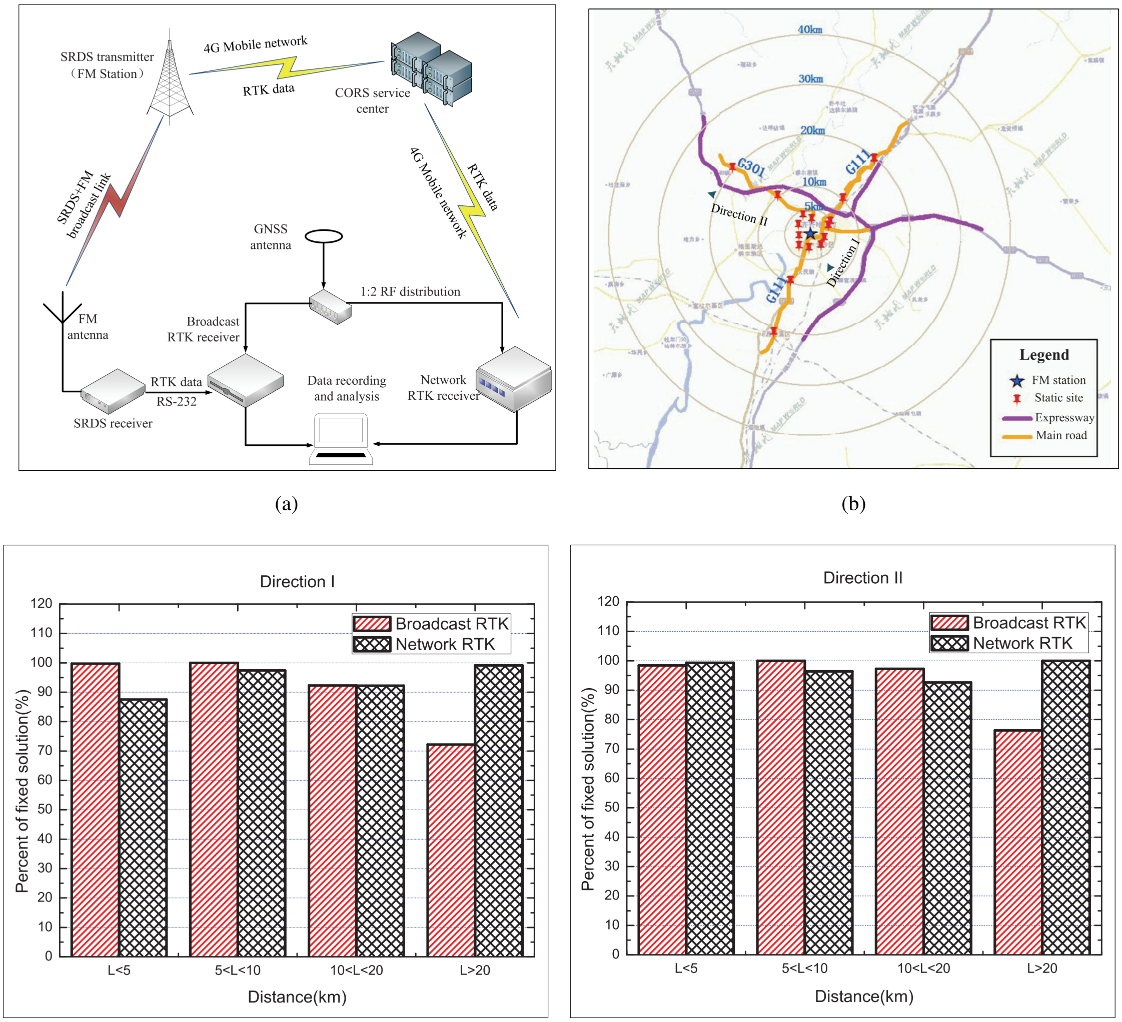
Power ratio	Left channel		Right channel	
	THD*	THD+N*	THD	THD+N
-14 dB	0.037	0.678	0.037	0.682
-17 dB	0.033	0.473	0.036	0.476
-20 dB	0.029	0.331	0.023	0.332
-23 dB	0.031	0.237	0.021	0.233
-27 dB	0.026	0.148	0.027	0.150
-30 dB	0.024	0.108	0.022	0.109

(b)

B. FM COMPATIBILITY TEST RESULTS

The interference of the SRDS signal on FM should be controlled to comply with the regulation on transmitter quality [12], which is objectively indicated by two indices: transmitter-side recovered sound SNR and distortion. As specified in [12], the worst transmitter-side SNR allowed is 60 dB, and the worst distortion allowed is 5%. For validation, we invited the Metrology and Test center of the Radio and Television State Administration of Radio, Film and Television of China to conduct a third-party test. Table 1(a) and Table 1(b) give the test results regarding the recovered sound SNR and the distortion, respectively. From Table 1(a) and Table 1(b), we can conclude that the effect on the FM system meets the national standard when the SRDS signal is of −17 dBm or less in power, as limited by the recovered sound SNR and the distortion.

The test also reveals that the sensitivity of the symbiotic broadcast receiver is −120 dBm@BER=1.7E-6 with a power ratio of −17 dB. The latest FM receiver chip from Silicon Labs has a sensitivity of 3.5 μV (−96 dBm with a 50-ohm load). Compared to such an FM receiver, the digital signal receiver actually has a 7 dB sensitivity margin when the power ratio is −17 dB. This confirms that the SRDS achieves an even wider coverage than FM.



(a)

(b)

(c)

(d)

FIGURE 6. **Broadcast RTK test results and their comparison with the Network RTK: (a) test setup; (b) test sites and roads; (c) percentage of fixed solutions under dynamic scenarios in Direction I; (d) percentage of fixed solutions under dynamic scenarios in Direction II.**

C. BROADCAST RTK PERFORMANCE

To evaluate the performance of SRDS broadcast RTK and compare it with the 4G network RTK, a third-party test was conducted by the National Geomatics Center of China (NGCC) at the city of QiQiHaEr, HeiLongJiang Province, China in March 2017. The setup of the test system is given in Fig. 6(a). Two commercial RTK rover receivers shared the GNSS signal from a single GNSS antenna: one obtained RTK data transmitted via SRDS with the transmitting FM station as a virtual reference station, and the other was from the 4G mobile network. The power ratio is −20 dB, and the SRDS transmitting power is 6 W. The results from both the rover receivers are recorded by a laptop computer.

The experiment collected data within a 40 km radius of the SRDS transmitting FM station. As shown in Fig. 6(b), the test collected data from 16 static sites and 7 different roads with 205 km in total length. The roads include main expressways and roads connecting downtown and the countryside. The collected data add up to 21070 GNSS epochs.

The positioning precision and reliability are of concern in the field experiment. We conclude that both the network RTK and broadcast RTK can achieve prominent positioning results under both static and dynamic scenarios. The results from broadcast and network RTK corroborate each other, with a maximum 3.2 cm horizontal deviation and 6.8 cm vertical deviation in all tests with the carrier phase fixed solution. We conclude that the SRDS broadcast RTK and network RTK achieve centimeter-level positioning.

In the field test, reliability is evaluated using the metric of the percentage of fixed solution under dynamic scenarios. The results are given by Figs. 6(c) and 6(d). The percentage of fixed solution of broadcast RTK is better than the network RTK when the distance of the test point from the transmitting FM station $L < 10$ km. The percentage of fixed solution decreases as L increases because both the performance of the SRDS receiver and the single reference station RTK system deteriorate as the receiver moves further from the transmitting station. This reveals the necessity to broadcast correction data from grid-based multiple VRS in the SRDS broadcast RTK; this approach is worth investigating in future work.

V. CONCLUSION

In this work, we proposed GNSS augmentation by radio symbiosis, which reuses existing FM infrastructure for next generation public PNT service. Authoritative third-party test results have proven its impressive performance in broadcasting RTK correction data for precise outdoor positioning. We are working on SRDS-enabled GNSS aiding technology, which is expected to achieve a higher GNSS receiver sensitivity than the prevailing mobile-Internet based A-GNSS. We are also working on SRDS-enabled time synchronization of ground positioning beacons, which is expected to enable GNSS-independent alternative PNT for GNSS-signal-blocked environments such as deep indoors. We believe that GNSS augmentation by FM radio symbiosis will be of great significance in the next-generation PNT infrastructure.

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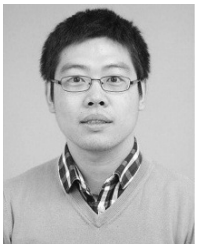

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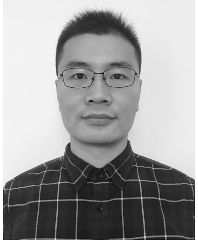

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