Performance of Hybrid Positioning System Combining GPS and Television Signals

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***Abstract*— In spite of the global coverage and the penetration into a daily life of GPS (global positioning system), GPS receivers have not been able to overcome the critical weakness of a GPS signal in indoor and urban areas due to its low signal power level after a long journey from satellites. One of the best solutions to this problem is the adoption of powerful terrestrial signals such as television, WiFi, and cellular communication signals. Among these signals, because TV transmitters have the highest level of signal powers, fixed geometries, and frequency diversities, TV signals are considered to be the strongest candidate as alternative ranging sources in urban and indoor areas. The combination of space-based signals such as GPS and land-based signals such as TV is ideal for a seamless universal positioning service, providing coverage to users in open spaces as well as restricted or closed space such as office buildings.**

To assess the benefits of a hybrid positioning system combining GPS and television signals, a prototype of TV signal based positioning systems and a GPS receiver are used for the positioning field tests in the San Francisco Bay area, where measurements sites are selected from indoor and outdoor areas in urban, suburban, residential, and rural regions. The performance of the hybrid system is presented across the categorized areas, showing the promising aspects of the combination of space signals and terrestrial signals.

I. Introduction

The introduction of GPS (global positioning system) has been revolutionizing the way of a life by providing accurate location information to the general public, information which had been a privilege of a few. On the hands of outdoor trackers, on the control panel of an airplane, on a police car chasing criminals, GPS receivers are found frequently and work as an essential guide, integrated deeply into our daily lives. Just as wrist watches had brought us freedom in a time domain, GPS has brought us freedom in a space domain.

However, the revolution has not been completed yet. Urban and indoor areas still have not been able to share the benefits of GPS, despite huge demands and commercial potentials in these regions. The main reason behind such an ironical situation is the low signal power levels of GPS signals transmitted from satellites more than 20,000 km away from a ground receiver. Because the signal levels are even below the natural thermal noise floor [17], [18], received GPS signals are hard to be recovered in harsh urban and indoor environments.

To survive in such harsh environments, we need a GPS-like signal with a higher power. First, other space-based signals—from space navigation systems such as Glonass and Galileo or from space communication systems such as Iridium and GlobalStar—are very similar to GPS signals, but share the same weakness of low signal powers due to their substantial physical distances from the ground. Second, there are land-based signals such as television, WiFi, and cellular communication signals. Many of these terrestrial signals are equipped with frame synchronization codes which are essentially equivalent to GPS spreading codes. Furthermore, terrestrial signals, by definition, come from nearby transmitters on the ground, traveling much shorter distances than GPS signals do. Hence, there have been heavy studies and investments on terrestrial positioning systems using TV [1], WiFi [8], [9], and cellular signals [5]–[7].

Among these candidate terrestrial signals, digital television signals are the closest match for our criteria because of their high power levels, being the focus of this paper. TV signals have an unlimited access to a ground power source, a resource which is scarcely available to satellite systems, and have higher transmission power limits than other candidate terrestrial signals. Because WiFi is supposed to work within a 100–200 m range and cellular signals are within their cell ranges not to interfere with neighboring systems, WiFi and cellular signals have a bottleneck of their own due to the system structures. In contrast, TV signals are FDMA (frequency division multiple access) signals spread over a wide range of frequency bands: 54–216 MHz and 470–806 MHz. This frequency diversity not only allows each TV broadcaster to transmit without the concern of interferences, but also it provides an additional strength against multipath errors because different channels experience different multipath, providing a better chance to resolve a multipath issue. Moreover, the locations of TV towers are fixed and well known, a benefit compared to GPS whose moving transmitters cause Doppler frequency shifts.

Currently, there are two types of TV signals in service: analog TV and digital TV signals. Digital TV systems are steadily replacing analog TV transmitters and are expected to be heavily deployed in urban areas. As digital TV standards, ATSC (advanced television systems committee) and DVB (digital video broadcasting) were adopted in the United States and European Union respectively [2], [3]. Because all digital and analog TV standards contain frame synchronization codes, we can use any TV signal for positioning with marginal adjustments on TV receivers, treating TV transmitting towers as GPS satellites on the ground. Since TV signals are not designed for positioning, there are a few technical challenges for these signals to be used as ranging sources: the absence of transmission time tags and poor transmitter clock stabilities. To solve these issues, an augmenting backbone network and a communication channel between a user and a network are required, common requirements for terrestrial positioning systems. These supporting systems provide aiding information to TV receivers and reduce the burden of position estimations by taking over a part of estimation processes.

As noted, TV positioning system (TPS) is one of the best candidates for urban/indoor positioning systems, because of its high power level and high availability in urban and indoor areas. However, in rural areas, GPS would provide a better accuracy than TPS because there is a less number of TV channels available. Therefore, the integration of TPS and GPS is necessary to provide a universal positioning solution covering the entire Globe including urban/indoor areas.

In this paper, we investigate the possibility of TV signals as ranging sources and the performance of a hybrid positioning system combining GPS and TPS through performance analyses and field tests in the following sections. The performances of GPS and TPS are analyzed in terms of signal powers, bandwidths, and error sources, providing the expected performance of each system in Section II. Following the description of the measurement equipments and sites of the field tests in Section III, the actual performance results are illustrated in Section IV. Finally, conclusions are given in Section V, in which the expected and observed benefits of hybrid positioning systems are summarized.

II. Performance Analysis

In this section, the positioning performances of GPS and TPS (TV signal based positioning system) are estimated by their signal specifications and by known error statistics. First, from a nominal transmission power and distance between receivers and transmitters, a signal to noise ratio (SNR) at a receiver is calculated. Then, the estimated SNR is converted into range domain errors based on the Cramer-Rao bound, providing a theoretical performance limit. Second, from the variances of known error sources to each system, range errors are reconstructed, describing more closely the actual system performances. These estimated system performances are later compared to the field test results in Section IV.

The theoretical performance limits of GPS and TPS can be derived from their physical conditions: transmission powers, path losses, and bandwidths. While GPS satellites have strictly limited on-board energy sources which are neither replaceable or expansible due to space and weight constraints, TV towers have accesses to almost unlimited energy resources, sending incomparably stronger TV signals than GPS signals. Furthermore, path losses are also not in favor of GPS, aggravating gaps between GPS and TPS. While GPS satellites are in the medium earth orbits (MEO) more than 20,000 km away from ground users, TV towers are normally less than 100 km away from urban users. Consequently, the path loss of TPS is significantly lower than that of GPS. In addition to the power factors, the broader frequency bandwidth of TV signals—5.38 MHz for TV and 2 MHz for GPS—widens the gap even more. Because of these physical advantages of TV signals, TPS services can penetrate into urban/indoor areas where GPS has not been able to cover.

The detailed signal power budgets in urban areas are given in Table I where we assume line-of-sight GPS signals and obstructed TV signals, an assumption favorable to GPS but conservative to TPS. The major differences come from transmission power—about 36 dB—and path losses. Path losses are calculated based on the log distance path loss model with the path loss exponents of 2 for GPS and 4 for TPS, again more conservative to TV signals.

$$P_{RX} = P_{TX} \frac{G_{TX} G_{RX}}{L_{air}} \left(\frac{\lambda}{4\pi d_0} \right)^2 \left(\frac{d_0}{d} \right)^n \tag{1}$$

where P_{RX} is a received signal power, P_{TX} is a transmitted signal power, G_{TX} is a transmitter antenna gain, G_{RX} is a receiver antenna gain, and L_{air} is an atmospheric loss. The GPS wavelength λ_{GPS} is 0.19 m and a nominal TV wavelength λ_{TV} is set to be 0.5 m from the range of 0.37–0.64 m corresponding to 470–806 MHz. d_0 represents the reference distance for a far field assumption and 1 km is a typical value for large scale systems like TV broadcasting. The distance between a transmitter and a receiver d is assumed 20,000 km for GPS and 100 km for TPS. The path loss exponent n represents the harshness of environments, determining signal degradations. n is known to be 2.7–3.5 in urban areas and 3–5 in shadowed urban areas [16]. Thus, the path loss exponent of 4 for TV signals represents a severe urban environment.

From (1), the received signal powers are obtained, with a difference of 50 dB between GPS and TPS. After applying noise powers and spreading gains, SNR could be calculated. TPS has a slightly higher noise floor, 4 dB higher than that of GPS, because of a wider bandwidth. Although a wider bandwidth hurts SNR, we will see that it eventually improves position accuracy in (2). The post-processing gain is composed of a despreading gain and an integration gain by the coherent integration of consecutive signal frames. GPS receivers despread the C/A code of 1023 chips, while TV receivers despread the frame synchronization code of 511 chips. Assuming the coherent integration of signals for 100 ms (corresponding to 100 frames for GPS and 4 frames for TPS), we finally obtain the post-processing SNR with a gap of 27 dB between GPS and TPS.

Based on the estimated SNR, the system accuracy limits can be calculated by the Cramer-Rao bound (CRLB) [11], [15], a bound for the standard deviation of range errors.

$$\sigma_\rho \geq \sqrt{\frac{1}{\gamma \beta^2}} \tag{2}$$

where ρ is a pseudorange measurement with a standard deviation σ_ρ, γ is a SNR, and β is a signal bandwidth. For a

TABLE I

SIGNAL POWER BUDGET IN URBAN AREAS

Power		GPS	TPS
TX Power		44.3 dBm	80.0 dBm
Loss & gain	TX antenna gain	10.2 dB	14.0 dB
	Path loss	182.4 dB	168.0 dB
	Atmospheric loss	0.5 dB	0.0 dB
	RX antenna gain	4.0 dB	0.0 dB
RX Power		-124.4 dBm	-74.0 dBm
Noise power	Thermal noise	-111.1 dBm	-106.7 dBm
	System noise figure	3.0 dB	5.0 dB
RX SNR		-16.3 dB	27.7 dB
Post-processing	De-spreading gain	30.1 dB	27.1 dB
	Integration gain	20.0 dB	6.0 dB
Post-processing SNR		33.8 dB	60.8 dB
User range error		3.1 m	0.1 m

fixed signal power, σ_ρ is inversely proportional to the square root of a signal bandwidth $\sqrt{\beta}$, after offsetting the increase of the noise floor. In other words, a wider bandwidth brings smaller position errors. The combined gain of the power and the bandwidth is equivalent to 36 dB SNR gain of TPS, emphasizing the physical superiority of TPS over GPS.

While the CRLB provides a fundamental view of the performance of positioning systems, a more realistic projection of system performances requires the considerations of other error sources: various environmental effects and system implementation issues [4]. In Table II, which is based on the known error statistics, clock stabilities, multipath, and transmitter geometries are the most significant contributors to position errors. First, because TV systems are not designed for positioning, TV transmitter clocks are not able to meet the level of stabilities equivalent to those of GPS atomic clocks, which are monitored and calibrated constantly by the vast network of ground stations. Second, observed GPS signals have a less chance of multipath than TV signals, because TV signals travel through ground paths. Third, less multipath errors in GPS signals means, however, the loss of multipath inflicted GPS signals and a fewer available GPS channels, while most TV signals are observable even under multipath environments. Fewer transmitters generates a worse geometry, represented by a higher HDOP (horizontal dilution of precision). As illustrated in Table II, first two error factors cause an equivalent level of range errors for TPS and GPS. However, due to better transmitter geometries, the position error of TPS (15.2 m) is expected to be less than a half of GPS position errors (34.0 m).

The signal power and error budget analyses have revealed the potentials of TPS compared to GPS. The physical advantages of TPS—power, bandwidth, and frequency diversity—provide a very promising accuracy as low as 0.1 m in a range domain, not feasible for a stand-alone GPS receiver. Even when the technical challenges, multipath and clock stabilities, are taken into accounts, the TPS performance is projected to be more than twice better than GPS. Furthermore, the technical advances in implementational issues are expected bring us closer to the theoretical goal given by the Cramer-Rao bound.

TABLE II

ERROR BUDGET IN URBAN AREAS [M]

Error source		GPS	TPS
Transmitter	TX clock	3.0	5.0
	System error	4.7	N/A
Transmission Path	Atmosphere	3.0	N/A
	Multipath	2.0	5.0
Monitor	System error	N/A	2.0
Receiver	System error	1.5	2.0
User range error		6.8	7.6
Geometry (HDOP)		5.0	2.0
User horizontal position error		34.0	15.2

In particular, the frequency diversity of TV signals is the brightest spot to mitigate the severest error: multipath.

III. FIELD MEASUREMENT CAMPAIGN

The projected system performances of TPS and GPS in the previous section are examined with the field test results from a measurement campaign in various environments. During the summer of 2005 in 37 selected sites in the San Francisco Bay Area, a hybrid positioning system was tested using the GPS L1 signal, analog and digital television signals as ranging sources. The measurement system, sites, and data collection method are described in this section, followed by the measurements results in the following section.

A. Hybrid Measurement System

Fig. 1 illustrates the configuration of the hybrid measurement system used for the field tests in the San Francisco Bay Area. The measurement system consists of two positioning sensors (a SiRF StarII GPS receiver and a Rosum TV positioning system), a notebook computer, and a GSM modem. The GPS receiver works independently from the rest of the system, generating GPS pseudorange measurements without any external aiding information. In contrast, the TV receiver depends on the connection with a position server. Because only a reception time can be measured at the TV receiver due to the lack of time tags in TV signal frames, external aiding information—the estimated transmission time of a TV frame—is necessary to construct TV pseudoranges. Therefore, the connection to a positioning server for aiding information is essential to the TV receiver. The communication among the receivers, the computer, and the GSM modem are established through serial connections, and the communication between the GSM modem and the GSM network is through GPRS (general packet radio service). The notebook computer delivers pseudorange measurements from both GPS and TV receivers to the position server and requests aiding information for the TV receiver. Although the requirement of aiding information to the TV receiver could limit its operational range, throughout the field test, GSM GPRS connection was proven to be robust and constantly available within the region of the San Francisco Bay Area.

In each measurement site, the hybrid measurement system was placed on a fixed location for an hour period. The two receivers were located side by side or on top of each other to

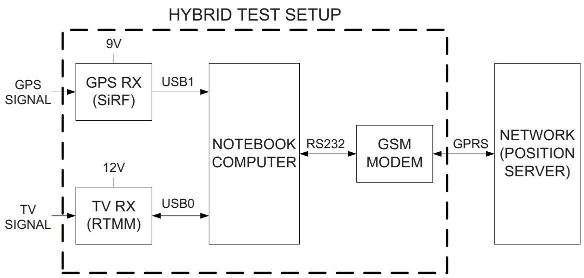

Fig. 1. Configuration of hybrid positioning measurement system

Fig. 2. Picture of hybrid positioning measurement system

minimize the physical distance between them. Fig. 2 shows the typical placement of the measurement system during the field tests.

B. Measurement Sites

Because of the variety of highly developed and crowded areas and pristine natural areas, the San Francisco Bay Area is an ideal place to test any positioning system and measure its performance in various environments. In this paper, we selected the measurements sites in 7 categorical areas: outdoor sites in urban, suburban, residential, and rural ares; and indoor sites in urban, suburban, and residential areas. Urban areas are the hardest environment for any type of positioning systems due to the multipath and blockage by buildings but have the extensive coverages of terrestrial communication signals such as TV signals; suburban and residential areas are relatively mild environments for both GPS and TV receivers with less obstruction by buildings and with a good coverage of TV signals; rural areas provide an unblocked open sky, best for GPS receivers but TV signals may not reach the every corner of rural areas where there are less commercial needs of them. Table. III displays the list of sites in each category.

The urban sites were selected from the San Francisco downtown where buildings create urban canyons, as shown in Fig. 3. Because only a small portion of sky is visible, the number of the observable GPS satellites were often less than 4, producing a low availability and a poor accuracy, while there was a significant number of the measured TV channels regardless of the obstruction of building structures. The urban indoor measurements were taken at the lower levels of 4–8 storied buildings located in the downtown area. The Palo

TABLE III

MEASUREMENT SITES IN SAN FRANCISCO BAY AREA

Category	Location	Outdoor	Indoor
Urban	San Francisco downtown	6	4
Suburban	Palo Alto downtown	4	5
Residential	Stanford graduate housing	8	5
Rural	Halfmoon Bay and Highway 280	5	N/A

Fig. 3. An urban site in San Francisco downtown (bottom-up view)

Alto downtown provided the suburban sites, an area with the combination of business buildings and dining places, as shown in Fig. 4. There are many 2–5 storied buildings, a few 10–15 storied buildings, and densely placed street trees. The residential sites were chosen from the Stanford graduate housing, an area with 2 storied wooden town houses, 10–15 storied concrete highrise apartment buildings, and wide open yards, as shown in Fig. 5. The wooden housings were shown to be less obstructive than concrete buildings, allowing GPS receptions outside and inside of those housings. The eastern region of the San Francisco Bay Area is a well preserved land with a small population and few buildings, supplying us the rural sites. 5 sites were selected from the Halfmoon Bay and the roadsides of the Highway 280, remote from residential and commercial areas as shown in Fig. 6. Due to their remoteness, a smaller number of television channels was observed. Detailed comparison between the categorized sites are given in the following section.

IV. RESULTS

During the field tests at the 37 measurement sites, we collected the GPS and TV pseudorange measurements. While the GPS measurements themselves are pseudorange measurements, the TV pseudorange measurements need to be constructed from the measured reception times of TV frames at the receiver and their estimated transmission times. After the construction of the TV pseudorange measurements, both GPS and TV pseudoranges are treated equivalently.

Because each measurement set was collected in a same fixed location for an hour, estimation results in different time frames share common information. Thus, estimation results would improve if previous estimations are taken into considerations with current measurement inputs. However, since such a feed-

Fig. 4. A suburban site in Palo Alto downtown

Fig. 5. A residential site in Stanford graduate housing

back scheme causes an unfair treatment of each measurement frame, in this paper, position estimations take no feedback information and are entirely based on current measurements, to produce statistically independent position fix results in a site. Readers should be noted that an real system implementation with a feedback scheme and filtering in a position domain would have a better performance than what are presented here.

Before comparing the position estimation results, it would be good to see an example of why the introduction of TV signals is important to urban/indoor positioning. In challenging environments such urban canyons and indoor areas, GPS signals are significantly blocked by surrounding building structures, producing poor or no fix at all. If we revisit the exemplary site in the San Francisco downtown, as shown in Fig. 3, only a narrow strip of the sky in a north-west direction is visible from a ground user. Therefore, because of the poor satellite geometry, the GPS fixes are scattered in a north-east direction, as illustrated in Fig. 7. On the contrary, because TV signals are able to penetrate through buildings and provide a reliable geometry, the TV fixes are well centered to the true position, as shown in Fig. 8. This example demonstrates the physical strength of TV signals in harsh urban environments.

For 3 dimensional positioning, we need at least 4 pseudo-range measurements. Although this requirement would not be a problem in an open area with 6–8 observable GPS satellites, a closed area often allows less than 3–4 satellites,

Fig. 6. A rural site in Halfmoon Bay

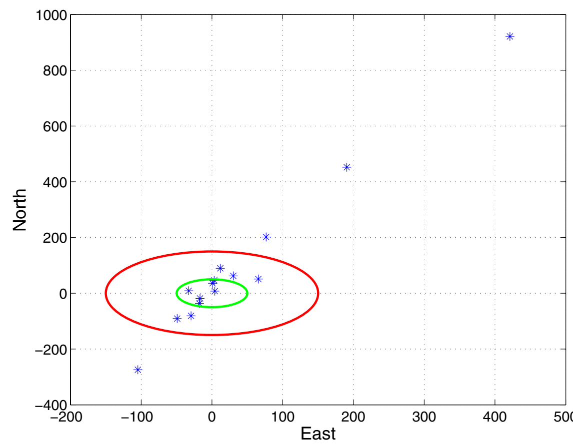

Fig. 7. An example of 3 dimensional GPS position fix results in an urban outdoor site [m] (Green and red circles, respectively, represent points 50 and 150 m away from the true position)

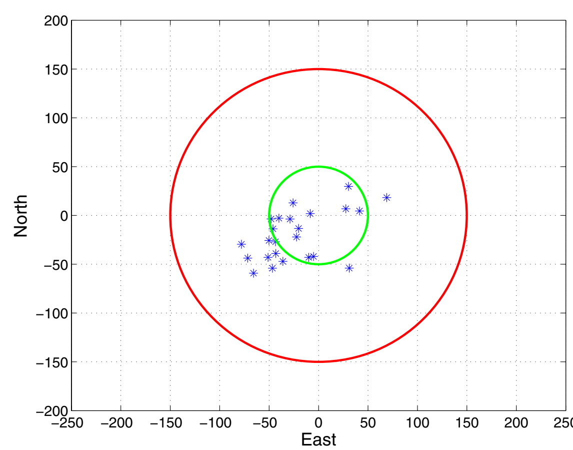

Fig. 8. An example of 2 dimensional TV position fix results in an urban outdoor site [m] (Green and red circles, respectively, represent points 50 and 150 m away from the true position)

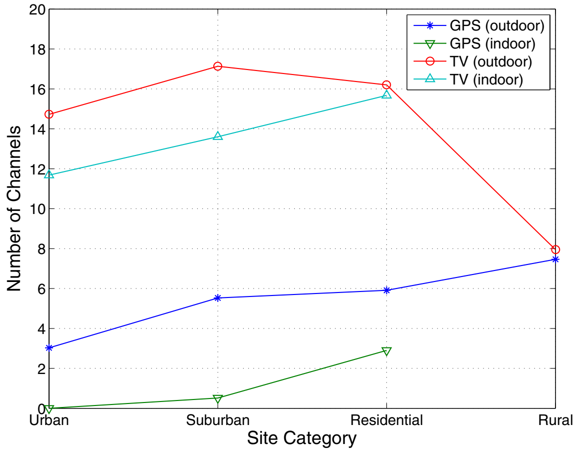

Fig. 9. Number of observed channels

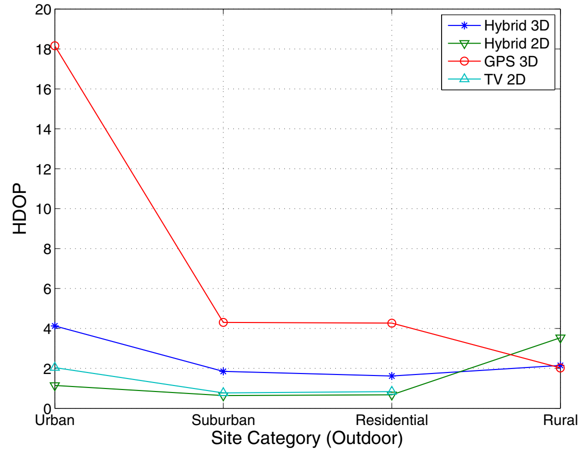

Fig. 10. Horizontal dilution of precision in outdoor sites

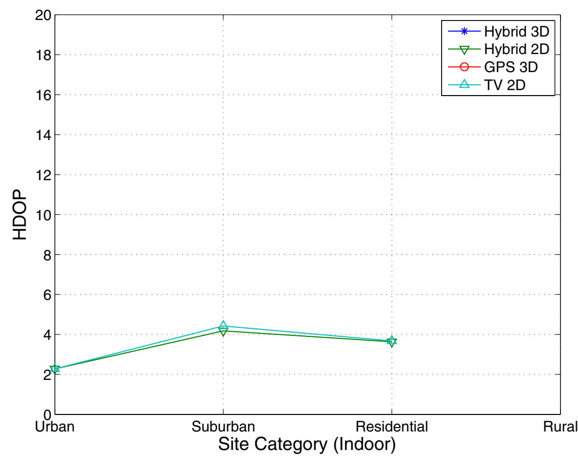

Fig. 11. Horizontal dilution of precision in indoor sites

disabling GPS systems in many critical areas. Therefore, the number of observed GPS and TV channels is one of the key indications of positioning system performances. Fig. 9 shows the average number of the observed channels in each category, from which we can see a significant increase in the number of available ranging sources by employing TV signals. Except the rural sites, there were more than 14 TV channels in average, guaranteeing a stable positioning service. The number of TV channels increases as we move from less populated rural areas to densely populated suburban and urban areas, because of the increasing commercial demands. On the contrary, the number of GPS channels increases in the order of the urban, suburban, residential, and rural sites. These contrasting patterns of GPS and TV channels clearly displays the advantage of the hybrid positioning integrating GPS and TV signals, particularly in the urban sites where only about 3 GPS channels were visible in average. When the addition of TV pseudoranges to GPS pseudoranges are beneficiary in the outdoor sites, TV pseudoranges are inevitable in indoor positioning where GPS pseudoranges are almost immeasurable in most cases.

DOP (dilution of precision) is a measure of the spatial diversity of ranging sources, providing a scale factor converting range domain errors to position domain errors. Therefore, it is another good way to estimate the improvement by the new ranging sources. As shown in Fig. 10 and Fig. 11, the HDOP is calculated in the four different positioning modes: hybrid 3D, hybrid 2D, GPS 3D, and TV 2D modes. The hybrid modes utilize both GPS and TV signals. In the outdoor sites, the GPS HDOP has a dramatic increase in the urban sites (about 18) from the rest of sites (less than 5), demonstrating its vulnerability in urban canyons. In contrast, the TV HDOP is in a very low range (less than 2) because of the large number of well spread transmitters. An interesting point is that the hybrid 3D mode has higher HDOP than the hybrid 2D when both of them use same transmitters. The reason is that 3D positioning has one more variable—the altitude—to resolve than 2D positioning which treat it as a pre-known constant. However, because the error in the known altitude could propagate into position solutions, position errors may not follow the same order of HDOP, depending on the quality of surveyed altitude database. In the indoor sites, the GPS HDOP is not available due to the lack of sufficient visible satellites, while TV maintains very low HDOP. Particularly, the HDOP of 2.3 is an impressively low number considering the harsh urban indoor environments.

While the number of channels and HDOP display the potential of hybrid positioning, success ratios and position error statistics can deliver the realistic view of the hybrid system, including the performance losses by multipath and clock errors. In this paper, multipath mitigation is assumed to be done in the receivers before pseudoranges are delivered. Clock errors have three components: receiver clock errors, transmitter clock errors, and transmission time estimation errors. First, because the GPS and TV receivers have separate clocks, there are two receiver clock biases to be resolved in position estimations. Even though a TDOA (time difference of arrival) scheme could remove these receiver clock biases, the performance of a TDOA scheme is expected to be worse than that of a TOA (time of arrival) scheme [12]. Therefore, TOA is adopted in this paper, keeping both receiver clock biases alive. In a future design of a hybrid system, it would be desirable to have a hardware synchronization between the two receivers, reducing one clock bias to have an even higher availability and better accuracy. Second, the nature of TV transmitter clocks is quite different from that of expensive GPS atomic transmitter clocks which are designed for positioning. Because TV clocks have enough qualities for broadcasting but not in the level of GPS clocks, TV pseudoranges inherit higher transmitter clock errors than GPS pseudoranges. Third, the transmission time estimation in TV positioning, as described in the previous section, is an additional error source to TV measurements.

In the presence of multipath and clock errors, an attempt of position estimations may not converge even when there are enough number of channels. Thus, least square residuals in a position solution are used to check the convergence of the solution, declaring a success or a failure in each epoch. More sophisticated RAIM (receiver autonomous integrity monitoring) algorithms can provide better filtering of high error fixes as well as exclude bad pseudorange measurements [13], [14], but are not covered in this paper, requiring further studies.

Fig. 12 displays the success ratios in the outdoor sites, illustrating the weakness of GPS in the urban sites and the weakness of TV in the rural sites. In the urban sites, the TV success ratio is about 20 % higher than that of GPS, a promising aspect of TPS. Given the fact that the average 14 TV channels were observable in the urban sites, the further improvement in TPS is expected when fault removal or exclusion methods are adopted in position estimations. In the suburban and residential sites, both TV and GPS performed well, while TV suffered in the rural sites due to the blockage of TV signals by mountains. Regions with less varying terrains would not see these types of blockage to TV signals. Interestingly, the hybrid modes often performed worse than the GPS-only mode or the TV-only mode, a phenomenon that is due to the lack of optimal GPS and TV weightings. When the GPS and TV weightings are known perfectly and optimally scaled to each other in the combined weighted least square positioning process, the hybrid modes should perform better than the individual cases. Better assessment of TV signal quality would lead us to an optimal scaling, based on constant monitoring of TV signals. Fig. 13 displays the success ratios in the indoor sites, where GPS was incapable of delivering any fix except in certain wooden residential buildings. Because all other concrete buildings quite entirely blocked GPS signals, only TV measurements were available in most cases where the hybrid 2D mode very closely follows the TV 2D mode. One can notice the unusually high success ratio in the urban indoor sites. However, this success ratio is not associated with a low error statistics, although generally there is high correlations between high success ratios and low error statistics. Actually, the urban indoor sites experienced the highest level of errors, indicating that this high ratio is the result of the imperfect convergence check algorithm. Certainly, tighter convergence check can improve the error statistics at the compensation of the success ratio.

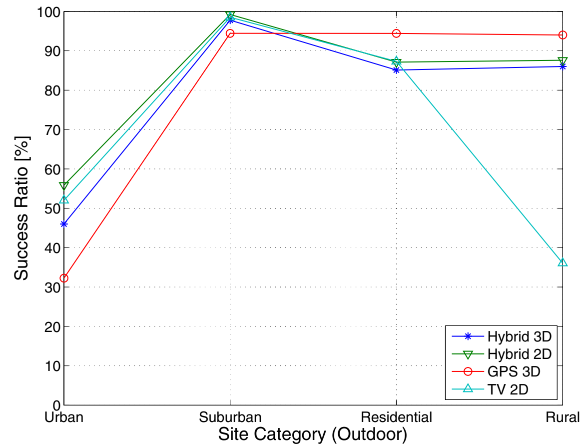

Fig. 12. Posfix success ratio in outdoor sites

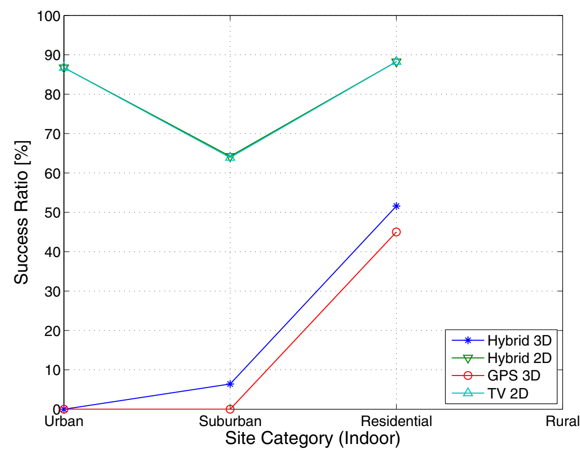

Fig. 13. Posfix success ratio in indoor sites

For the fixes having passed the convergence check, the horizontal position estimation errors are calculated and given in terms of CEP (circular error probable), the median of error statistics. In Fig. 14 and Fig. 15, estimation errors show a decreasing pattern as we move from harsher environments to more benign environments. In the urban sites, while the CEP for GPS and TV are 84 m and 94 m respectively, those for hybrid 3D and hybrid 2D are 49 m and 48 m, significantly decreased from the individual system cases. This improvement highlights the importance of the hybridization in urban sites. In the indoor areas, only TV positioning generates meaningful fixes with the CEP of 73 m, and 71 m for the suburban, and residential areas respectively. The urban indoor sites experience a high CEP of 355 m, which is the result of the loose convergence check algorithm. Because a high success ratio with high errors means that many bad fixes were not filtered properly, a lower error statistics is expected with a tighter convergence check algorithm.

In this section, the field test results of the hybrid positioning system equipped with a GPS receiver and a TV positioning

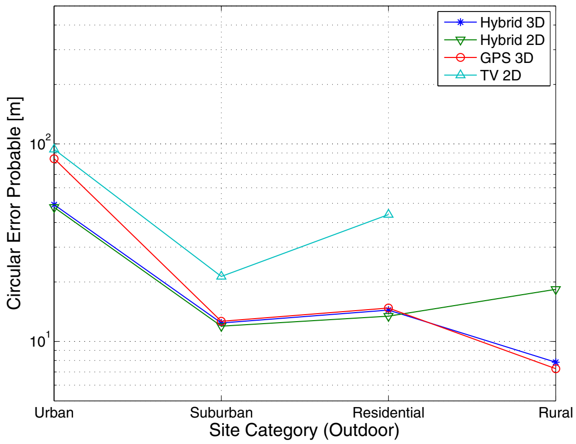

Fig. 14. Circular error probable in outdoor sites

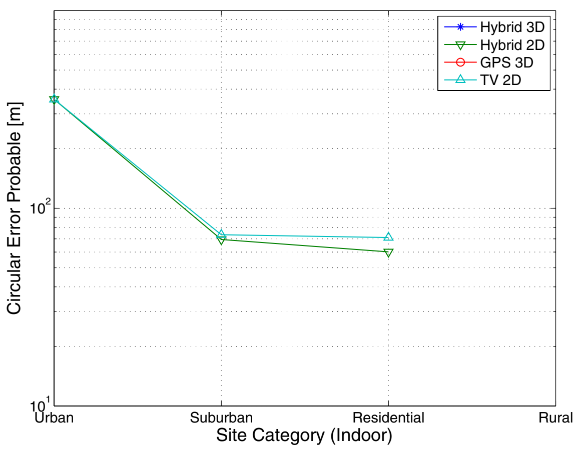

Fig. 15. Circular error probable in indoor sites

device have been presented in various measures: the number of observed channels, the quality of transmitter geometries represented by HDOP, the success ratio of position estimations, and the position error statistics represented by CEP. As expected, the physical strength of TV signals enabled TV signals to penetrate into almost any place in the San Francisco Bay Area. These TV signals were observed in the large numbers, providing very good geometries with low HDOP, while GPS satellites suffered significantly in the urban sites and virtually disappeared in the indoor areas. However, at the same time, the success ratio and the CEP showed the issues in multipath mitigation and channel screening algorithms. Although these problems are not pursued in this paper, further improvements are certainly expected, based on the high benefit of TV positioning and its integration with GPS.

V. Conclusion

This paper has presented a new promising positioning technology based on television signals for a seamless positioning service in urban/indoor areas. Despite the high commercial demands for positioning services in these areas, there has been little success to provide a reliable service, because these harsh environments so well obstruct signal propagations. In particular, GPS signals substantially lose accuracy and availability. To overcome these challenges, it is necessary to adopt terrestrial signals with a higher power and a wider bandwidth, such as television signals. Television signals are the best alternative ranging sources, because of frequency diversity in addition to their power and bandwidth.

In this study, we have examined the possibility of TV signals as ranging sources by theoretical analyses and field tests. Both from the analyses and the field tests, the potentials of a TV signal based positioning system (TPS) have been demonstrated. By the Cramer-Rao bound, the theoretical limit of ranging errors has been predicted as low as 0.1 m. During the field tests, around 15 and 12 TV channels were observed in the urban outdoor and urban indoor sites respectively, while there were 3 and 0 observed GPS channels in the corresponding areas. However, technical challenges also have been revealed. The actual accuracy of TPS has been shown not to meet the physical limit and the success ratio was not enough to provide uninterrupted positioning, results that are supposed to be caused by multipath errors and transmission time estimation errors.

Despite these technical challenges, significant improvements are anticipated in the performance of TPS receivers, because of the physical advantages of TV signals: a high power, a wide bandwidth, and a frequency diversity. Furthermore, its integration with GPS receivers is expected to reinforce both systems and open a door to universal positioning services, covering anywhere and anytime. To achieve such a goal, further studies are requested in the characterization and calibrations of the TV error sources and the relative weightings between TV pseudoranges and GPS pseudoranges.

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