ANALYSIS OF THE SIGNALS OF OPPORTUNITY AND COOPERATIVE BASED POSITIONING FOR UAS NAVIGATION IN DEEP URBAN AREA

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Abstract

Autonomous navigation of most unmanned aircraft systems (UAS) is entirely dependent on GNSS. However, in deep urban area, the weak signal of Global Navigation Satellite Systems (GNSS) can be easily lost, thus UAS has no other reliable means of navigation. For this reason, autonomous navigation or surveillance like Unmanned Aircraft System Traffic Management (UTM) in deep urban area remains as a challenging problem. To tackle this problem, there have been great interests in positioning using signals of opportunity (SOP) including such as Long Term Evolution (LTE). More recently, a software defined radio for LTE positioning demonstrated a successful UAS flight test with a few LTE base stations.

Although there are usually plentiful LTE base stations in urban area, they are primarily deployed to provide coverage to mobile communication users such that the base station network layout is subject to be suboptimal for positioning. And, it is not certain that SOP based on LTE could provide an appropriate positioning performance to safely navigate in deep urban area. This paper investigates the positioning performance of the current network of LTE base stations and the required augmentation of the SOP network to meet desired positioning accuracy in deep urban area of Seoul, South Korea. The paper also considers DSRC as another possible SOP ranging source and looks into the benefit of cooperative positioning with nearby UAS.

Introduction

It is well known that Global Satellite Navigation Systems (GNSS) signals are not reliable in indoors and urban area, and there has been active research on developing alternative positioning means to enable positioning service during GNSS outage. Among many possible alternatives, the Long Term Evolution (LTE) based positioning has recently been considered as a promising signals of opportunity (SOP) [1-5] due to a large number of LTE base stations and novel technologies that overcame the drawback of positioning reference signal (PRS) by using cell-specific reference signal (CRS). The ranging accuracy with the CRS-based time of arrival extraction technique has shown to be around 10 meters.

The Unmanned Aircraft System Traffic Management (UTM) considers LTE as a communication channel, which would justify the use of LTE as an alternative positioning means. In addition to LTE, researchers of UTM proposed to use a Dedicated Short Range Communication (DSRC) at 5.9 GHz for ground-to-air and/or air-to-air communications [6]. The DSRC has been used as a communication device in automobile industry, and there have been efforts in using DSRC as ranging sources for positioning as well [7,8]. The obtainable ranging accuracy using DSRC was claimed to be up to a couple of meters from several tens of meters depending on ranging methods and signal-to-noise ratio. The coverage of a DSRC transceiver is reported to be around 1000 m, which seems to be adequate coverage range in urban area [9].

Therefore, UAS in the future may be equipped with LTE and DSRC, and those can serve as a positioning sensor. Although LTE and/or DSRC-based positioning is possible, it is necessary to check if they are practical and reasonable solutions for UAS navigation and surveillance in deep urban area. For this analysis, the paper evaluates the positioning accuracy using the current deployment of LTE network and how much augmentation is needed to meet a certain positioning accuracy in virtual city modelling environment in Seoul, South Korea. For the augmentation of the LTE network, this paper will use DSRC transceivers because their ranging accuracy is higher than LTE with a lower cost. Additional DSRCs will be placed in optimal locations through our sensor network optimizer tools. In addition, the benefits of cooperative positioning based on a DSRC or Ultra Wideband (UWB) ranging between neighboring UAS will be investigated.

The paper will first review the state of the arts in LTE and DSRC positioning. Then, the virtual

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modelling of a deep urban area in Seoul, South Korea is introduced. The discussion of the optimal DSRC augmentation technique will be followed and the recommended network augmentations in the interested area of Seoul and theirs positioning performance will be presented. After evaluating the benefits of cooperative positioning with nearby UAS, conclusions will be followed.

Opportunistic Ranging Sources

To enable a positioning in deep urban area, various opportunistic ranging sources have been proposed including television, Wi-Fi and GSM/CDMA [10]. Among them, LTE is preferred because of its agile accessibility and enough geometric diversity with plentiful transceiver stations located in urban area, and also for its high signal strength and large bandwidth.

LTE signals are composed of primary synchronization signal (PSS), secondary synchronization signal (SSS), reference signals, data signals and control signals [11]. Navigation tracking performance on a ground vehicle using LTE synchronization signals and reference signals based on TOA estimation method showed 5.36 m RMSE error compared with GPS navigation solution [12] and simulation on TDoA positioning with LTE signal showed 5 m RMSE positioning accuracy characterized by Cramer-Rao Lower Bound [13].

Range measurements for positioning also can be attained from nearby vehicle with additional ranging sources. Then, the location of UAS is calculated through lateration by collected range measurements [14]. For two-way wireless radio communication among moving vehicles, DSRC is widely used for its efficiency, robustness and wide coverage. Range estimation using DSRC periodic broadcast message with nearby vehicles demonstrated ranging accuracy around 2 m without clock synchronization, which was similar accuracy compared with TWR method [8]. To overcome multipath effects, UWB also can be combined as an additional ranging source with wide bandwidth provided with its centimeter level of range accuracy.

Positioning Accuracy with LTE Base Stations of Deep Urban Area in South Korea

To evaluate the positioning performance in deep urban area, a virtual city model was constructed based on the Gangnam subway station intersection which is located at 396, Gangnam-daero, Gangnam-gu, Seoul, South Korea. In this region, a total 35 LTE base stations were identified as shown in Figure 1.

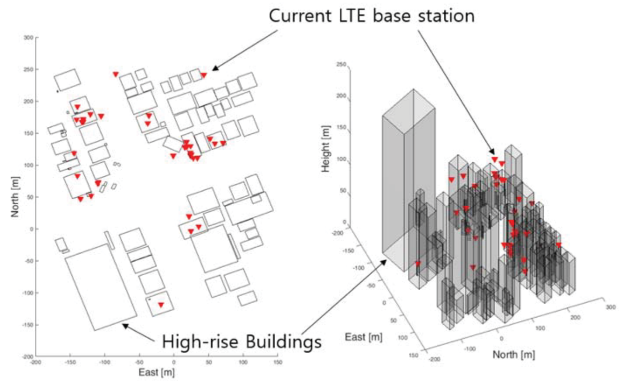

Figure 1. Virtual City Model and LTE Base Stations of the Intersection of Gangnam Subway Station in Seoul, South Korea (provided from Prof. Jiwon Seo in Yonsei University)**.**

Figure 2 shows the simulated horizontal positioning accuracy at 150 ft above ground using all of the base stations in Figure 1. The positioning accuracy (PA) was estimated from [11]

$$\boldsymbol{P} = (\boldsymbol{A}^T \boldsymbol{W}^{-1} \boldsymbol{A})^{-1} \quad (1)$$

where $\boldsymbol{A}$ is a geometric matrix between ranging sources and a user. $\boldsymbol{W}$ is a covariance matrix of the ranging sources and is assumed as

$$\boldsymbol{W} = \begin{bmatrix} \sigma_{LTE,1}^2 & 0 & 0 & 0 \\ 0 & \sigma_{LTE,2}^2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \sigma_{DSRC,n}^2 \end{bmatrix}. \quad (2)$$

Note that Eqn. (2) assumes time of arrival ranging measurements for the simplicity of the analysis and a LTE base station is only used when it has a line of sight to a flight space or UAS. Figure 2 also shows 5σ (99.999%) confidence ellipse of the positioning accuracy derived from ***P*** matrix from Eqn. (1) at the five UAS locations. Note that 5 σ (99.999%) confidence ellipse is chosen as a safety bound to protect against any collisions in this paper. As shown in Figure 2, the positioning accuracy (1 σ) lies between 5 m to 30 m and four of the confidence ellipses of the five UAS locations overlap with the buildings, which indicates that the risk of collision with the surrounding buildings may be larger than 0.00001 % due to positioning errors. Therefore, it can be seen that LTE base stations with 10 m ranging accuracy alone may not be an adequate positioning infrastructure for UAS navigation in deep urban area, and there is a need to augment LTE positioning network. This paper will investigate an optimized hybrid LTE/DSRC positioning network layout that minimizes a total number of ranging sources while meeting a desired positioning accuracy.

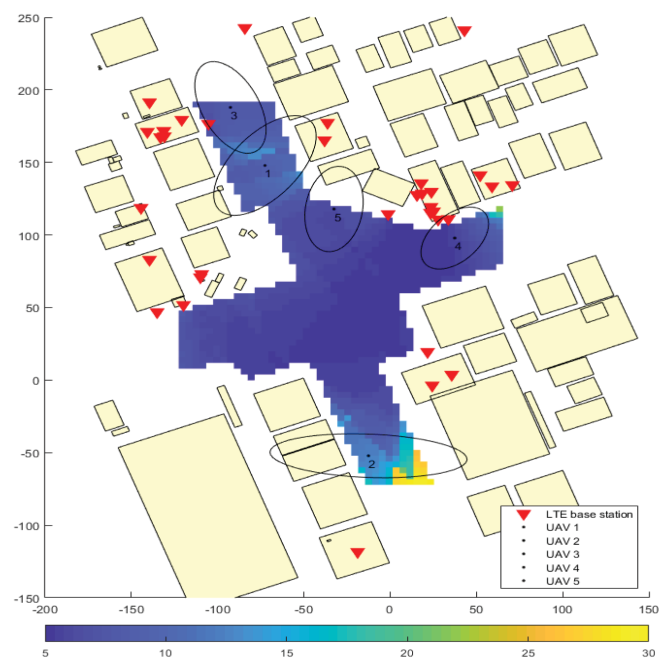

Figure 1. Horizontal Positioning Accuracy and Confidence Ellipses (99.999%) at Five UAS with 35 LTE Base Stations

Planning of Optimized DSRC Augmentation and Hybrid LTE/DSRC Positioning Performance

The LTE base stations are an expensive infrastructure and would be primarily deployed to provide the coverage for mobile communication. Therefore, the layout of the base station network may be suboptimal for a navigation purpose and requires an augmentation to the network. Because the DSRC is a more cost effective ranging source than an LTE base station, this paper will place additional DSRC transceivers to the existing LTE network.

Figure 3 shows existing LTE base stations, the grids of the candidate DSRC locations, and flight space on 2D plane, respectively. Figure 4 shows the locations of LTE base stations and candidate DRSC transceivers in 3D on buildings. Figure 5 shows the flight space at 150 ft above the ground and surrounding buildings. As shown in Figure 3, the candidate DSRC locations were placed along the main streets to allow good line of sights between the candidate DSRC locations and flight space. For the additional DSRC placements, the ranging accuracies of LTE and DSRC are assumed to be 10 m and 2 m, respectively. The DSRC placement algorithm was developed by modifying the previous coverage analysis method proposed in [10].

The coverage analysis method uses a binary integer linear programming and seeks for the minimum number of additional ranging sources to the existing network that satisfies the desired positioning accuracy. The baseline formulation of the binary integer linear programming is

$$\begin{aligned}
&\min Z = \sum_{i=1}^{n} w_i x_i = \mathbf{w}^T \mathbf{x} \\
&\text{subject to: } \mathbf{Ax} \geq \mathbf{b} \\
&\qquad \mathbf{Cx} \leq \mathbf{d} \\
&\qquad \mathbf{Fx} \leq \mathbf{g} \\
&\qquad \mathbf{w}^T \mathbf{x} \leq Z_{\min} \\
&\qquad x_i \in \{0,1\}
\end{aligned} \tag{1}$$

where Z is the cost function to be minimized. $\boldsymbol{x}$ is a column vector consisting of (0, 1), which is the binary index of the candidate station grids. If a vector element of $\boldsymbol{x}$ is equal to 1, then the corresponding DSRC location element is chosen. $\boldsymbol{w}$ is the waiting factor for each vector element and is lower for the current LTE base stations to maximize the use of the existing infrastructure. The matrix $\boldsymbol{A}$ is a visibility matrix between a candidate ranging source location grid to a flight space grid. The matrix $\boldsymbol{A}$ also consists of 0 and 1. The visibility matrix is constructed by using the digital map of Seoul. The vector $\boldsymbol{b}$ is a column vector and its elements are the minimum number of ranging source to be seen at each flight space grid. The matrix $\boldsymbol{C}$ is a ranging source separation matrix that prevents from selecting closely located DSRCs. The column vector $\boldsymbol{d}$ is the maximum number of DSRC locations within a designated bound. The matrix $\boldsymbol{F}$ has the previous solution sets, and the element of the column vector $\boldsymbol{g}$ should have an integer value less than the number of chosen grids in the previous solution sets. The matrix $\boldsymbol{F}$ and the vector $\boldsymbol{g}$ enforces a unique solution in searching for a valid solution set. $Z_{\min}$ is the minimum cost in a valid solution set.

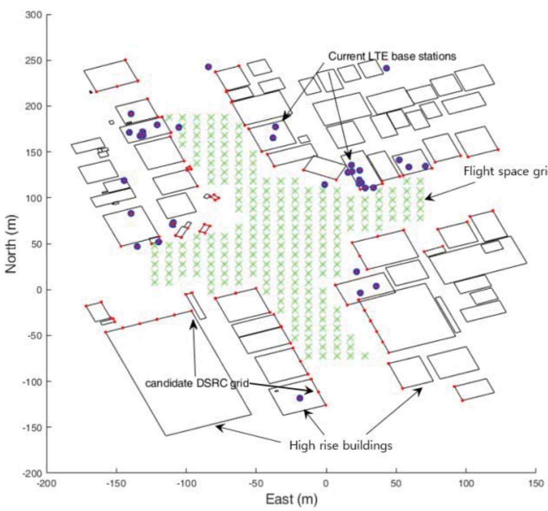

Figure 3. Current LTE Base Stations, Candidate DRSC Location, and Flight Space on 2D Plane in Gangnam, Seoul, South Korea

The binary linear programming formulation iteratively find a valid solution set that meets the required positioning accuracy in all of the flight space. The tighter the required positioning accuracy is, the larger number of DRSC transceivers would be needed. Table 1 lists three required positioning accuracies and the resultant optimized hybrid positioning network with the selected current LTE base stations and new DSRC transceivers. The hybrid positioning networks are shown from Figure 6 to Figure 8, and the corresponding positioning performance is shown from Figure 9 to Figure 11. Compared with the previous positioning network which utilizes deployed LTE base station solely, the optimized hybrid LTE/DSRC positioning network provides much better positioning accuracy and smaller confidence bounds with a lower number of ranging sources.

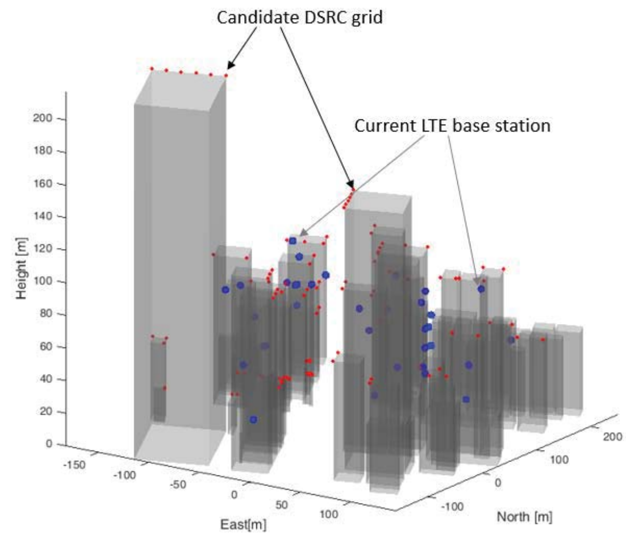

Figure 4. Current LTE Base Stations, Candidate DSRC Location in 3D on Buildings in Gangnam, Seoul, South Korea

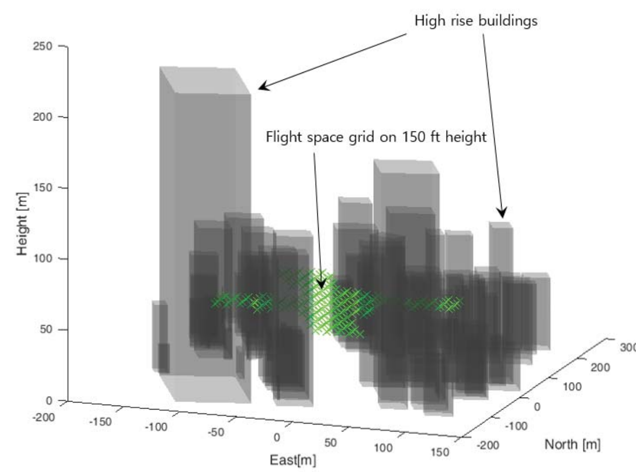

Figure 5. Flight Space at 150 Ft Above Ground and Surrounding Buildings in Gangnam, Seoul, South Korea

Table 1. The Number of Ranging Sources to Meet the Required Positioning Accuracy (BILP Results)

Required Positioning Accuracy (2σ)	Total number of ranging source	Number of LTE base stations	Number of new DSRC transceivers
4 m	17	4	13
6 m	12	4	8
8 m	9	3	6

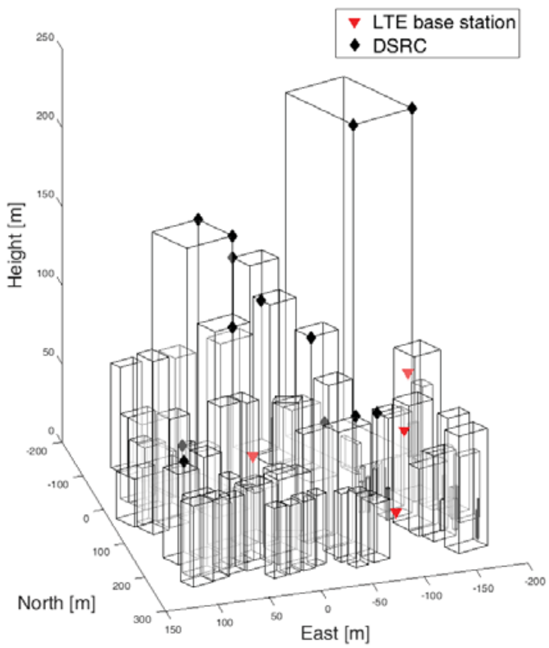

Figure 2. Resultant Anchor Locations Which Meets 4m Positioning Accuracy (2σ)

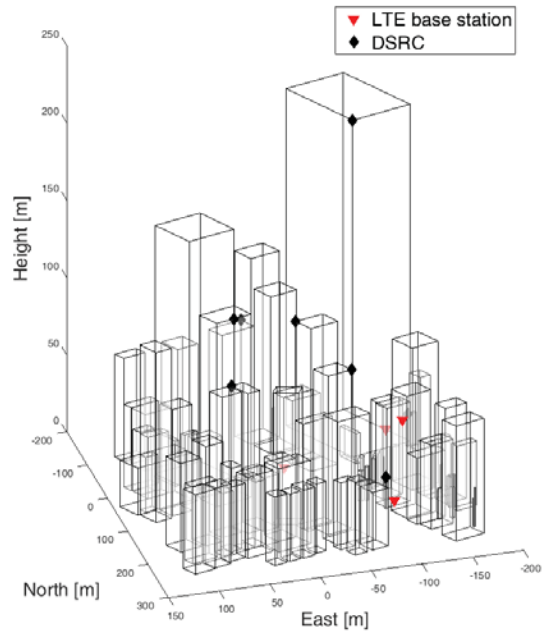

Figure 3. Resultant Anchor Locations Which Meets 6m Positioning Accuracy (2σ)

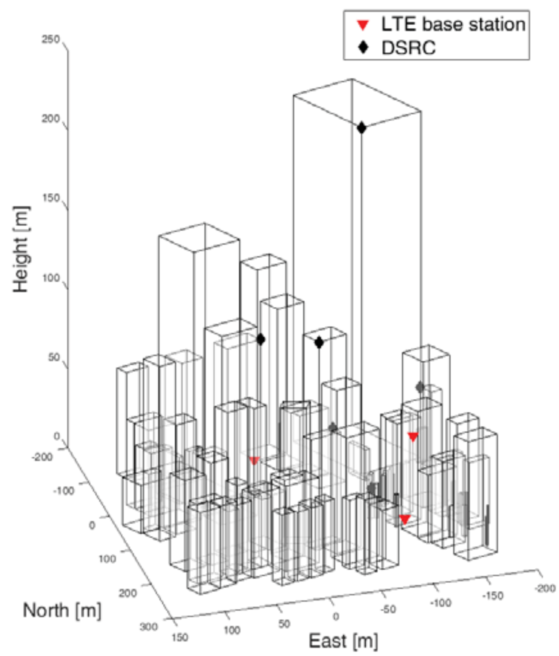

Figure 4. Resultant Anchor Locations Which Meets 8m Positioning Accuracy (2σ)

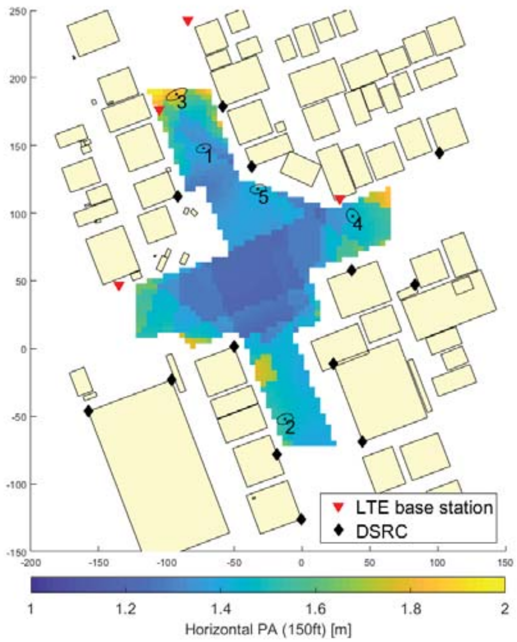

Figure 5. Positioning Accuracy and Confidence Ellipses of Five UAS from the Optimized Positioning Network (2m, 1σ)

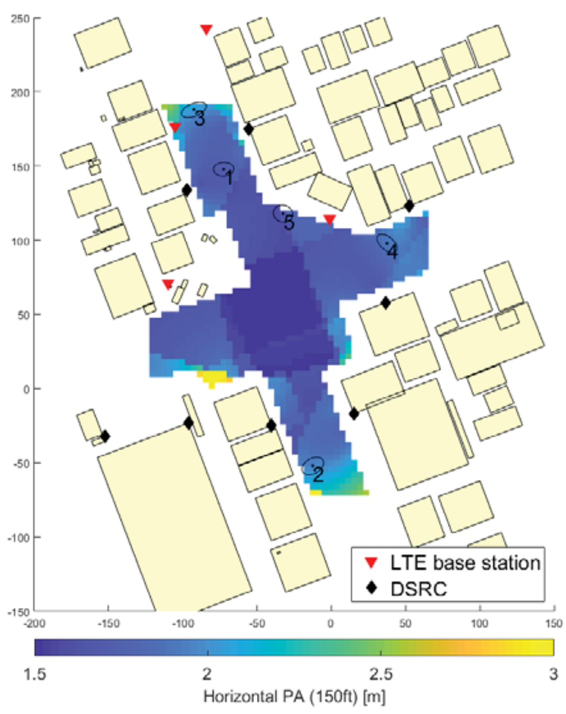

Figure 6. Positioning Accuracy and Confidence Ellipses of Five UAS from the Optimized Positioning Network (3m, 1σ)

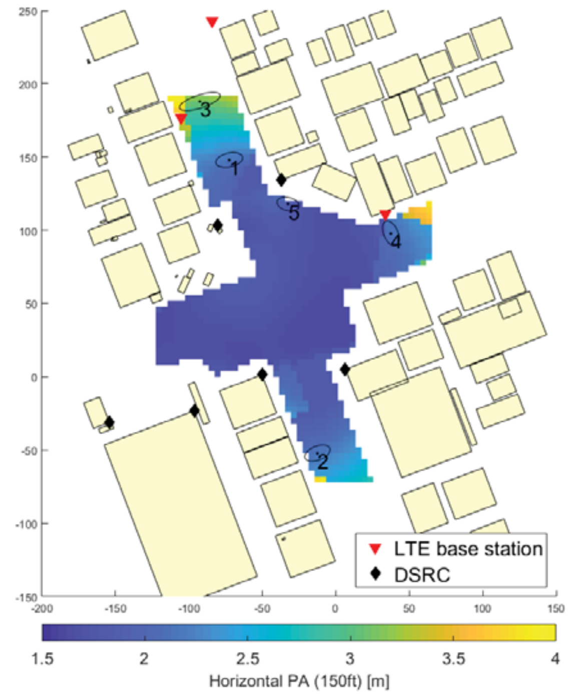

Figure 7. Positioning Accuracy and PB of Five UAS from the Optimized Positioning Network (4m, 1σ)

Cooperative Positioning

Cooperative positioning uses other vehicles as ranging sources in addition to LTE or the hybrid LTE/DSRC. The expected benefit of the cooperative positioning is that UAS may improve positioning solution when there are multiple UAS in view as well as a positioning network. For the cooperative positioning, UAS is assumed to be able to use DSRC with 2 m ranging accuracy or UWB with 10 cm ranging accuracy in this paper. The total ranging accuracy in this method also takes into account the positioning uncertainty of the other UAS to be used as a ranging source. Cooperative positioning in deep urban area requires an initial position of UAS and an it is provided from other positioning means such as LTE or LTE/DSRC hybrid positioning network. Figure 12 compares the positioning accuracy of the current LTE network, LTE/UWB cooperative positioning (CP), and LTE/DSRC CP with five UAS. Figure 13 shows the positioning accuracy of the proposed LTE/DSRC network (4m, 1σ), LTE/UWB CP, and LTE/DSRC CP. In these examples, the cooperative positioning improves positioning accuracy more than four times compared to the optimized hybrid LTE/DSRC network.

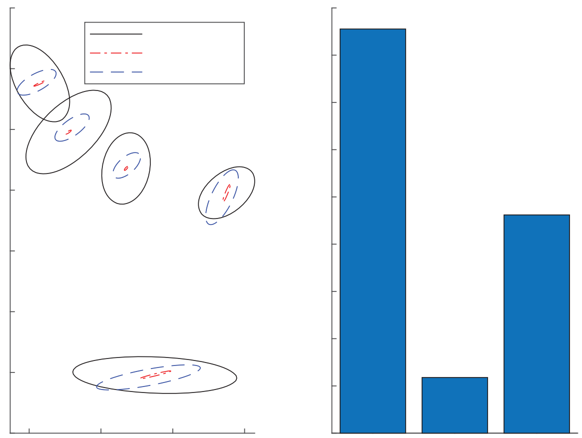

Figure 8. Comparison of Positioning Accuracy of Five UAS in Current LTE and Cooperative Positioning with DSRC and UWB.

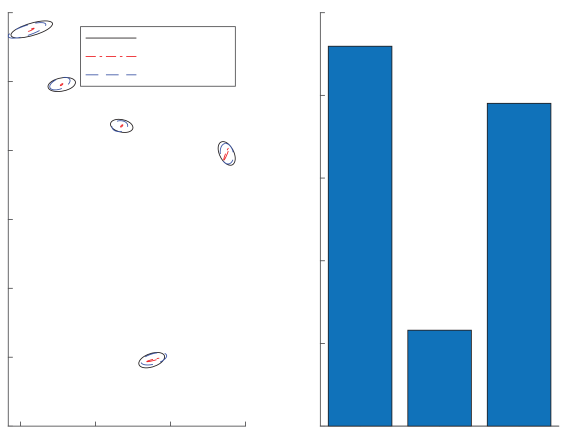

Figure 9. Comparison of Positioning Accuracy of Five UAS in the Proposed Hybrid LTE/DSRC Network (4m, 1σ) and Cooperative Positioning with DSRC and UWB.

Conclusions

This paper presented the analysis of UAS positioning performance at 150 ft above ground in deep urban area by using signals of opportunity of LTE, DSRC, and UWB. The positioning performance was assessed with the modelled urban environment and ranging accuracies of LTE, DSRC, and UWB reported in literatures. The analysis based on the selected urban area and LTE ranging accuracies suggests that UAS navigation with LTE alone may not provide enough safety during navigation due to the lack of positioning accuracy. The hybrid optimized LTE/DSRC networks, which place additional DSRC transceivers and use a few LTE base stations, could effectively and efficiently help UAS to fly more safely. When there are multiple UAS that intend to navigate closely in deep urban area, the cooperative positioning among UAS with UWB may significantly improve positioning accuracy as shown in results.

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