Hybrid CFO-RSS Cooperative Positioning for Environments with Limited GNSS Visibility

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***Abstract*— Cooperative Positioning (CP) techniques are used to enhance the performance of positioning through sharing position-related data among a number of agents. These agents are usually users with mobility and, possibly, the infrastructure node(s). In CP systems, position-related data are shared among the participating nodes using a communication medium. Inter-node distance is a common parameter considered in CP techniques, especially for those in the environments with limited Global Navigation Satellite System (GNSS) visibility including dense urban areas and indoor environments. Radio ranging based on Received Signal Strength (RSS) is popular among researchers for its simplicity. However, the accuracy of this method is far beyond the requirements of CP systems. Here, we introduce Carrier Frequency Offset (CFO) as a potential observable to improve RSS ranging. Regardless of the content of the data communicated among the agents, RSS and CFO always exist in the communication signal. Therefore, the results of this work can be applied to improve the performance of any other CP method. Here, a hybrid CFO-RSS ranging method is presented to improve the accuracy of RSS ranging. The experimental results show up to 80% accuracy improvement over RSS using the proposed hybrid CFO-RSS technique. Although the examples used here are for outdoor situations, the outcomes are directly applicable indoors or any situation where GNSS signals are not available.**

Keywords- CFO; Cooperative Positioning; GNSS; RSS

I. Introduction

Global Navigation Satellite Systems (GNSSs), for example the Global Positioning System (GPS), are worldwide utilities to address the positioning requirements of different civilian and military applications. However, problems of limited availability and degraded accuracy in some environments decrease the reliability of GNSS for many applications. Cooperative Positioning (CP) methods can be considered as an appropriate approach to addressing the shortcomings of GNSS. CP techniques are generally based on sharing position-related data among a number of mobile or stationary nodes to improve the availability and accuracy of positioning. Differential GPS (DGPS), Satellite-Based Augmentation System (SBAS), and Ground-Based Augmentation System (GBAS) [1] are examples of conventional CP systems which are developed for GPS-based positioning accuracy enhancement. However, these techniques are functional only when the GPS signal coverage is sufficient for standalone positioning. Addressing the constraints of conventional CP methods, modern CP methods have also targeted positioning enhancement for areas with limited signal visibility. Figure 1 shows an example of a situation in which a modern CP is used for positioning or positioning accuracy enhancement.

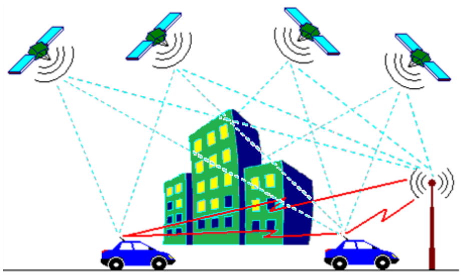

Figure 1. An example of a modern CP system

In this example, the left vehicle, with limited visibility of the GPS signals, fuses the data received from a neighbouring vehicle and/or a Road Side Unit (RSU) for positioning. Figure 1 is only an illustration of a modern CP system and the number and type of the nodes do not imply any specific technique. For indoor or undercover areas, we can consider only inter-node communication for CP purposes. What is stressed here is the position-related data inherent in Vehicle-Vehicle (V-V) and Vehicle-Infrastructure (V-I) communication signals. These data, apart from the content being communicated, can be used for radio ranging and range-rating among the nodes. Fusing these data for CP purposes is the distinguishing factor between modern and conventional CP techniques [2]. Modern CP methods generally rely on range or range-rate data among the participating nodes and using GNSS signals if available. For more convenience, unless conventional CP is stressed, CP implies modern CP for the rest of this article.

Some examples of range-based CP systems for situations with limited visibility of GNSS signals are presented in [3-7]. The details of these methods are out of the scope of this article but the common issue among these methods is Received Signal Strength (RSS) ranging, assumed to be available for CP

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purposes. The other common radio ranging techniques included are Time of Arrival (TOA) and Time Difference of Arrival (TDOA). Explaining the details of time-based techniques is not in the scope of this article. However, the important issue is the unrealistic assumptions made by researchers on achievable ranging accuracy using these methods. In the related literature, including those mentioned above, it is usually assumed that the distances among the participating nodes in a CP system can be estimated with accuracies under 10 *m* using radio ranging methods. However, in [8], it is explained that achieving that level of accuracy is technically very complex for time-based techniques, and effectively impossible using RSS. In this article, the technical and accuracy limits of RSS-ranging are explained followed by presentation of a novel approach to mitigate RSS shortcomings using Carrier Frequency Offset (CFO) of the inter-node communication signal. The results of this work show that the achievable ranging accuracy using the proposed hybrid method is suitable for CP purposes especially those CP methods used in areas with limited GNSS signals and which use inter-node range data for positioning.

In Section II, the proposed hybrid technique is explained followed by simulation results in Section III. Section IV discusses the experimental results and concluding remarks are presented in Section V.

II. HYBRID CFO-RSS RANGING

A. RSS for ranging

RSS is very popular for radio ranging due to its simplicity but it is very inaccurate. The following equation is mostly used to model the channel loss and is the basis for the RSS technique [9, 10]:

$$P_r(r) = P_0 - 10q\log(r) \quad dBm \tag{1}$$

In (1), r is the distance between transmitter and receiver, P_r is the power of received signal, and P_0 is a known constant which can be calculated based on the received power for a known distance in a calibration process. The key parameter here is the Path Loss Exponent (PLE), q. The PLE determines the level of signal attenuation in a communication channel and varies between around 2 for suburb areas (open space) and around 4 for urban canyons with dense construction [11] and between 2 and 3 for indoor cases [12]. The exponential characteristic of this coefficient causes large errors in distance estimation if it is not assigned properly. In a dynamic environment, q varies randomly due to the changing spatial relationships to obstacles and objects. Therefore, PLE must be estimated for ranging. In [13-16], some PLE estimation methods are presented which can estimate PLE with a specified level of error. A typical PLE estimation error, reported in those works, can lead to significant ranging errors, even more than 100%, as is explained in [8].

In this work, we will focus on the value added by CFO through the hybrid CFO-RSS ranging method presented. Therefore, we simply assume PLE to be a constant, 2 for open areas, and investigate the inaccuracy of RSS ranging and how CFO can improve. The simulation and experimental results confirm that the hybrid CFO-RSS ranging approach significantly improves radio ranging so that it can be a viable substitute for RSS-based ranging in CP techniques.

B. CFO for range-rating

The range-rate between a transmitter and receiver can be estimated based on the Doppler Effect. In our previous works, it was shown that the Doppler shift is a suitable observation for CP purposes in terms of viability and complexity [8, 17-19] . Equation (2) represents the Doppler Effect for electromagnetic waves.

$$\frac{dr}{dt} = c\left(1 - \frac{receive\ carrier\ frequency}{transmit\ carrier\ frequency}\right) \tag{2}$$

where c is the speed of light. According to (2), the range-rate can be estimated, measuring the received frequency for a known transmit frequency. In practice, the actual transmit and receive frequencies are not known due to clock drift in the transmitter and receiver. Therefore, CFO includes both Doppler shift of the received signal and the effect of clock errors. As is explained in [18], we have

$$\dot{r} = \frac{dr}{dt} = -\left[\frac{CFO - \delta_r - \delta_t}{f}\right]c \tag{3}$$

where f is the nominal transmit frequency, δ_t is the frequency offset of the transmitter clock, and δ_r is the frequency offset of the receiver clock. According to (3), CFO can be used for range-rating and range-rate-based CP provided clock errors are known. In [19, 20], some examples of these CP methods and the techniques to estimate clock errors are presented. Here, we assume that clock drifts are known using one of those techniques and focus on fusing CFO data with RSS to improve ranging for CP purposes.

C. CFO-RSS fusion for ranging enhancement

CFO contains range-rate data which can be added to RSS to mitigate ranging errors. Here, we propose an Extended Kalman Filter (EKF) [21] to fuse RSS and CFO data. For this, the dynamic state vector θ and system are modelled as

$$\theta(t+\tau) = F\theta(t) + G\zeta \tag{4}$$

where τ is the period of communication packets, F is the system transition model, G is the system noise model, and ζ is the system noise. We have

$$\theta = \begin{bmatrix} r \\ \dot{r} \end{bmatrix},\ F = \begin{bmatrix} 1 & \tau \\ 0 & 1 \end{bmatrix},\ G = \begin{bmatrix} \tau \\ 1 \end{bmatrix} \tag{5}$$

In (5), it is assumed that the range-rate between the receiver and transmitter is constant over the period of communication packets, for example at τ =0.1 *s* or τ =0.01 *s*. This is a valid assumption when considering the dynamics of pedestrian receivers or vehicles in normal driving conditions.

For the observation model, we have

$$Z = \begin{bmatrix} RSS \\ CFO - \delta \end{bmatrix} + \gamma \tag{6}$$

In (6), γ is the observation noise, CFO is a linear function of

$\dot{r}$, Equation (3), and RSS is a nonlinear function of r, Equation (1). So, for the EKF, we consider the Taylor expansion of (1) around the last estimate of the state vector to form the linear observation model. This leads to

$$Z' = H\theta + \gamma \quad (7)$$

where

$$Z' = \begin{bmatrix} RSS - P_0 + 10q\left(\frac{\ln(r^-) - 1}{\ln(10)}\right) \\ CFO - \delta \end{bmatrix} \quad (8)$$

and

$$H = \begin{bmatrix} \frac{-10q}{r^- \ln(10)} & 0 \\ 0 & \frac{-f}{c} \end{bmatrix} \quad (9)$$

In (8), r^- is the range estimate from the previous epoch, q is assumed to be a known constant, and $\delta = \delta_r + \delta_t$ is assumed to be known through using the methods referred to earlier. Considering q as a constant is generally a false assumption because it depends on the environment, which is generally dynamic. However, to keep the focus of this work, we accept the error induced by this assumption to avoid the complexities of mixing PLE estimation and CFO-RSS fusion and leave that for future work.

To complete the required parameters for EKF, we need the covariance of observation errors, R, and the covariance of system noise, Q. From (4), $Q = GG^T\sigma_\zeta$, where σ_ζ is the Standard Deviation (STD) of the range-rate modelled. Assuming a normal condition for the user dynamics (no skidding, no severe shaking, etc.) σ_ζ is considered to be a low value, 0.1 *m/s*. For R, we have

$$R = \begin{bmatrix} \sigma_{RSS}^2 & 0 \\ 0 & \sigma_{CFO}^2 \end{bmatrix} \quad (10)$$

where σ_{RSS} and σ_{CFO} are the STD of RSS and CFO observation noises respectively. For this work, σ_{RSS} and σ_{CFO} will be set based on the characteristics of the transceivers employed for this research, explained in the next sub-section.

D. Communication Medium

The communication medium considered for the proposed technique is one channel of the Dedicated Short Range Communication (DSRC). DSRC has a bandwidth of 75*MHz* in the 5.850 to 5.925 GHz band and 7 channels, assigned for vehicle-vehicle and vehicle-infrastructure communication by U.S. Federal Communications Commission (FCC) [22]. Similarly, the European Telecommunications Standards Institute (ETSI) and Japanese Association of Radio Industries and Businesses (ARIB) have dedicated a bandwidth for such communication. A pair of DSRC transceivers which can log the RSS and CFO for the received packets will be used to verify the performance of the proposed technique. These transceivers can transmit and receive DSRC packets with different power level, packet rate, and payload. The measurement results using these transceivers when located at precisely known locations shows that CFO and RSS observation noise is around 125 *Hz* and 3 *dBm* respectively. These values will be used to set the EKF parameters and generate simulation data.

III. Simulation Results

To analyse the performance of the proposed hybrid ranging method, two types of simulation were conducted. In the first simulation, a single trial was conducted. For this, a transmitter was considered to be placed at the origin of a 2D coordinate system, here North-East (NE), and receiver travels through a 200 *m* random trajectory with the speed of 10 *km/h* receiving the packets broadcast by the transmitter at the rate of 100/*s*. The speed is set low, covering the pedestrian case and creating a pessimistic condition for CFO observations in which observation noise is high compared to Doppler shift [19]. The PLE is initially set to 2 but it randomly jumps on 2.3 for a few seconds. This is a simple simulation of the dynamic nature of PLE to check the performance of RSS-based ranging and the effect of CFO on ranging enhancement through CFO-RSS technique. Figure 2 shows the trajectory of the mobile node.

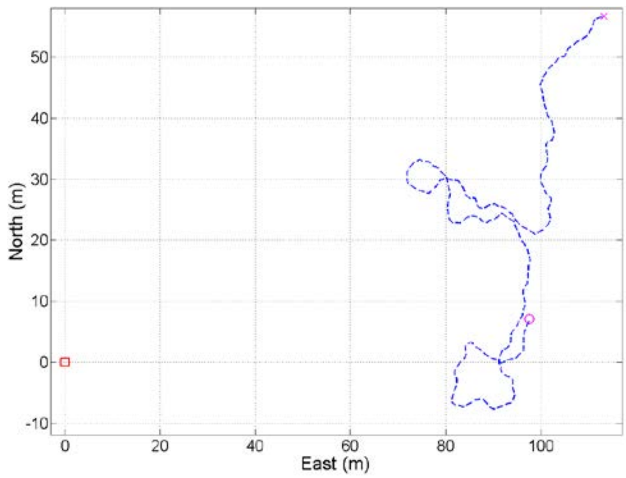

Figure 2. A random trajectory for a single trial

For performance analysis, the ranging error is defined as $\hat{r} - r$ where $\hat{r}$ is the range estimated by the EKF. Figure 3 shows the performance of ranging methods for the single trial. As can be seen, the hybrid technique outperforms RSS-based ranging. In this figure, the spikes of RSS ranging belong to the timeframes, randomly selected, that PLE is changed from 2 to 2.3. The RSS ranging which assumes PLE is 2 shows a significant error due to this little change in PLE. This shows the vulnerability of RSS ranging to uncertainties of PLE. However, as can be seen, adding the CFO data, which contains range-rate information, to ranging process reduces the ranging error induced by PLE uncertainties.

It is worth mentioning that for RSS-based ranging, the STD of CFO observation is set effectively to infinity, a very large number in MATLAB, to eliminate the innovation of CFO observations in Kalman filtering. This is effectively equivalent to removing CFO observations from the ranging process. In Figure 3, the Root Mean Square Error (RMSE) of RSS based ranging is about 24.4 m and RMSE of CFO-RSS method is about 8.6 m. An improvement metric, μ, is defined to show the amount of ranging enhancement achieved through fusing CFO data in raging process. This parameter is defined as

$$\mu = \left[1 - \frac{RMSE_{CFO-RSS}}{RMSE_{RSS}} \right] \times 100 \quad (11)$$

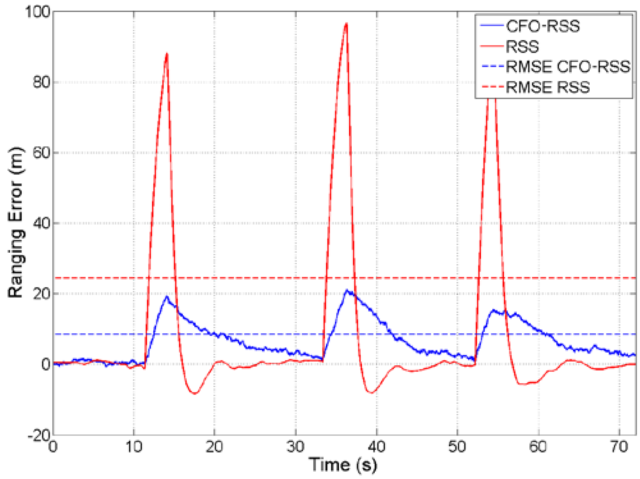

Figure 3. Performance of RSS and CFO-RSS ranging

This parameter shows that hybrid CFO-RSS technique led to 65% ranging accuracy improvement over RSS-based ranging.

For the next simulation, a statistical analysis is performed. Also, the effect of CFO observation noise is investigated. For this, the CFO observation noise is assumed to be zero-mean Gaussian and its STD is varied between 50 *Hz* and 200 *Hz*. For each level of CFO noise, 5000 trials are conducted with random trajectories and other parameters set as those for the previous single trial. Figure 4 shows the average RMSE over 5000 trials for RSS and CFO-RSS at different levels of CFO observation noise.

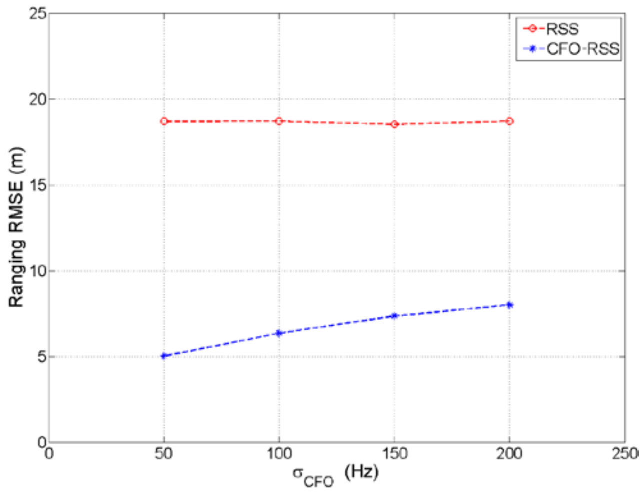

Figure 4. Performance of CFO-RSS ranging for different levels of CFO observation noise

In this figure, superiority of hybrid method over RSS-based ranging is evident and, as can be seen, CFO-RSS performs better when the CFO observation noise is weaker. Depending on the level of CFO noise, Figure 4 shows ranging improvement between 57% to 73%.

The simulation results confirm the validity of the hypothesis that fusing CFO data with RSS leads to radio ranging accuracy enhancement. To verify the viability of the hybrid CFO-RSS ranging, some experiments are conducted which are explained in the next section.

IV. Experimenal Results

To verify the performance and viability of the proposed method, an experiment was conducted at Showcase Cinema car park, Nottingham, UK. Although the proposed method can be considered for indoor and undercover areas, the outdoor situation was selected for two reasons. The first was to facilitate centimetre-level Real Time Kinematic (RTK) positioning of the nodes for use as ground truth reference data. The second was for synchronization of data logged in the DSRC receiver and RTK position estimates for comparison purposes. The DSRC transceivers used in this experiment, from Cohda Wireless™, have a GPS input. Using GPS signals, the DSRC receiver tags the received packets in Coordinated Universal Time (UTC) seconds.

For the transmitter, a stationary node was set up to broadcast DSRC packets at the rate of 100/*s*. A DSRC receiver was set up on a vehicle which travelled around the trajectory depicted in Figure 5.

Figure 5. Transmitter (red square) and trajectory of the mbile reciver (original photo from Google Maps)

The mobile receiver was logging the RSS and CFO of the received packets. Simultaneously, two RTK GPS receivers logged the GPS signals. These data were post processed to calculate the real position data of the mobile node and position of the transmitter. Two rounds of experiments were conducted. In the first run, the transmit power were set to 10 *dBm*, 50% of maximum power. For the second round, the transmit power was set to 20 *dBm*, the maximum.

Figures 6 and 7 show the experimental results of the hybrid CFO-RSS and RSS ranging for 10 *dBm* and 20 *dBm* transmit power respectively. In these experiments, PLE was assumed to be constant, 2, and as can be seen, the RSS ranging error is very large for the areas where obstacles, trees in our case, change the PLE. However, fusing CFO data with RSS reduces the ranging error significantly. The RMSE of the two ranging techniques for two experiments are summarized in Table I.

TABLE I. EXPERIMENTAL RESULTS FOR RANGING ERROR USING DIFFERENT TECHNIQUES

Ranging Technique	Ranging RMSE	
	Transmit Power: 10 *dBm*	Transmit Power: 20 *dBm*
RSS	25.8	27.8
CFO-RSS	7.5	5.1
μ (%)	71	82

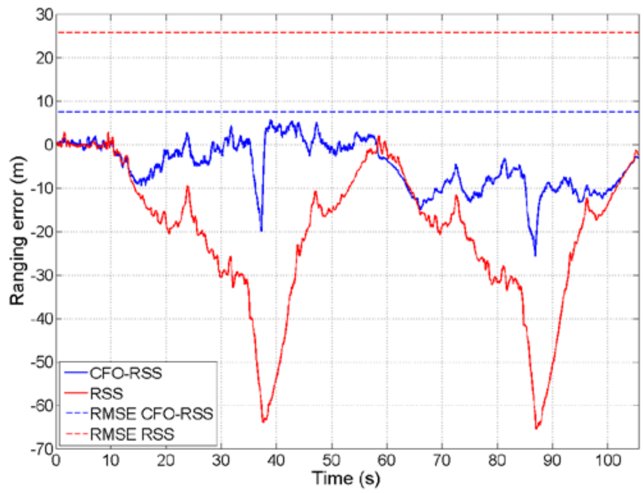

Figure 6. Ranging error comparison, transmit power 10 *dBm*

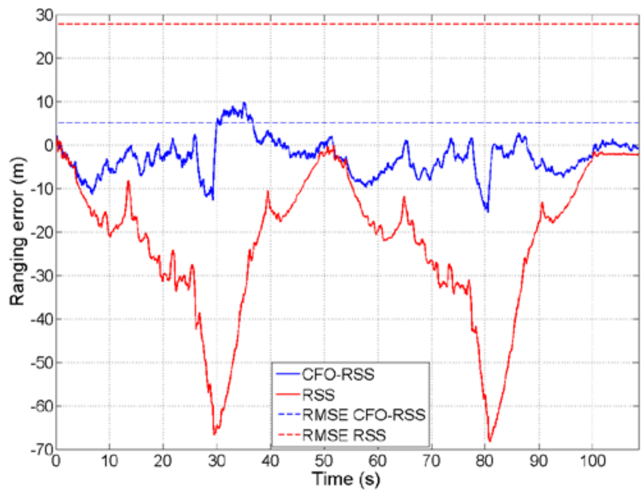

Figure 7. Ranging error comparison, transmit power 20 *dBm*

As can be seen, fusing CFO and RSS improves ranging accuracy by about 70% to 80%. Increasing the transmit power increases the improvement factor, μ, because the comparative level of CFO observation noise declines when transmitting power increases [23, 24], i.e. signal-to-noise ratio increases.

V. CONCLUSION

The concept of modern Cooperative Positioning (CP) was introduced. CP techniques are considered for positioning enhancement in different situations including the environments with limited visibility of Global Navigation Satellite System (GNSS) signals. Radio ranging is an important contributor to CP techniques and the Received Signal Strength (RSS) ranging method is popular among the researchers due to its simplicity. However, the achievable ranging accuracy using the RSS method is not useful for many CP purposes. The Carrier Frequency Offset (CFO) of the inter-node communication signal was introduced as an observable that can improve RSS-based radio ranging. A hybrid CFO-RSS ranging method was proposed. Using an Extended Kalman Filter (EKF), this novel technique fuses CFO and RSS data to enhance the performance of RSS-based radio ranging. The simulation results showed how the hybrid method outperforms the RSS ranging. Also, experimental results verified the viability of the hybrid method and showed 70% to 80% of ranging accuracy improvement over RSS ranging.

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