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A time-recordable cross-layer communication protocol for the positioning of Vehicular Cyber-Physical Systems

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HIGHLIGHTS

- We proposed a new time-recordable back-off algorithm.
- A complete cross-layer communication protocol is proposed for vehicular positioning.
- We evaluate the proposed algorithm by ranging experiments.
- The proposed algorithm is practically feasible and is superior to OSS-TWR.

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ABSTRACT

Vehicular Cyber-Physical Systems are a rapidly growing research field that has applications in a variety of locations that include urban centers, underground parking lots, as well as tunnels environments. These systems require real-time or constant location information, but the traditional satellite signal-based positioning systems do not work well in tunnels or urban centers with dense skyscraper due to satellite signal Non-Line-Of-Sight (NLOS) problem. The One-Sided Synchronous Two-Way Ranging (OSS-TWR) algorithm can remedy the imprecise positioning of satellite signal-based positioning systems by using a Dedicated Short Range Communications (DSRC) link between the vehicle and Road Side Units (RSUs). However, the unavoidable network collisions in these wireless communication systems will severely influence the measurement of the signal flight of time, thus significantly degrading positioning estimation accuracy of OSS-TWR. In this paper, a cross-layer communication protocol is proposed to enhance OSS-TWR by compensating for the impact of network collision. Firstly, OSS-TWR positioning algorithm is analyzed and the reasons for the poor precision location estimation are further explored. Secondly, a time-recordable back-off algorithm is proposed that can record the total back-off time for a frame resend resulting from a network collision. Following this, the experimental ranging results show that the proposed algorithm is practically feasible and is superior to OSS-TWR.

1. Introduction

Vehicular Cyber-Physical Systems (VCPS), namely systems that aim to improve vehicular active safety and infotainment, have attracted a significant amount of interest over the past few decades [1–4]. In a VCPS, each vehicle is considered as a smart object equipped with a powerful multi-sensor platform, communication technologies, computation units, as well as IP-based connectivity to the Internet and to other vehicles either directly or indirectly [5,6]. The vehicular communications in a VCPS are also known as Vehicular Ad Hoc Networks (VANETs) and include Vehicle-to-Vehicle (V2V), Vehicle-to-Road (V2R), Vehicle-to-Human (V2H) and Vehicle-to-Sensor (V2S) communications [7, 8].As a result of the convenient information exchange in VANETs, several new vehicular applications such as active safety applications [9], vehicular real-time monitoring, self-piloting automobile, and location-based services (LBS) [10], have appeared. Importantly, these applications have a common requirement for

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precise vehicular position information. In vehicular active safety applications such as cooperative collision avoidance or warning systems [11,12], the position, direction and speed is shared among vehicles to help to predict potential hazards and take appropriate steps to decrease the probability of an accident [13,14]. In security monitoring system, the vehicular real-time location is acquired without interruption. Other LBS such as advertisement recommending system also utilize the vehicle position to promote or target advertisements. Overall, the precise vehicular position plays an important role in these VCPS applications [15–17].

Usually, the position of the vehicle can be obtained using a GPS receiver. However, in some special environments (such as in tunnels, underground parking lots, urban centers with dense high buildings), the satellite-based positioning system does not function well and does not offer precise position information as the satellite signal is shielded [18]. Therefore in order to maintain smoothy operation in a VCPS system, it is vital that solutions are explored to enhance vehicular positioning accuracy in these environments. With advances in DSRC, a ground-based positioning system based on wireless radio signals can be employed [19,20]. In order to acquire position information in **these** special environments, a novel energy-saving OSS-TWR algorithm was proposed in [21]. This OSS-TWR algorithm could remedy imprecise positioning for environment where the satellite signal was blocked. However, this method does not consider the influence of the delay time brought about by wireless network collision, and hence will result in an imprecise distance measurement. Importantly, it is widely known that this collision is unavoidable in wireless communication systems [22].

The main contribution of this paper is to propose a new cross-layer communication protocol to alleviate the influence of wireless network collision. Firstly, the problems associated with OSS-TWR are outlined and potential network collisions are discussed. In this discussion, it is highlighted that the delay time of frame resending is a key factor that influences the positioning accuracy. Secondly, a time-recordable back-off algorithm is designed to record the total back-off time for frame resending. Thirdly, a cross-layer communication protocol is proposed for vehicular positioning based on the time-recordable back-off algorithm.

This paper mainly focuses on how to acquire precise position information for VCPS applications in satellites signal shielded areas. In Section 2, some state-of-the-art vehicular positioning methods are introduced. Section 3 presents an analysis of the problems with the existing OSS-TWR algorithm while Section 4 proposes a time-recordable cross-layer protocol to enhance the OSS-TWR positioning precision in satellite signal shielded areas. Section 5 outlines a ranging experiment to verify the validity of the proposed algorithm. Section 6 employs the proposed method in a practical application. Finally, this paper draws important conclusions from the presented material as well as discusses some issues and future avenues of research.

2. Related works

Accurate and reliable vehicle localization is a key component of VCPS applications such as active vehicle safety systems, real-time estimation and forecast of traffic conditions, and vehicular monitoring. Traditionally, GPS receivers are utilized for navigation but its positioning accuracy is unable to meet the requirements of new emerging VCPS applications. Fortunately, researchers have developed solutions to help enhancing the positioning accuracy. In [23], Jesse Levinson and Sebastian Thrun presented a probabilistic map-based vehicular positioning method. Their approach employed maps as probability distributions over urban environment properties rather than as fixed representations of the environment at a snapshot in time. This approach can increase the positioning accuracy. A metric-topological hybrid map-based navigation method was addressed in [24], and could be used for self-piloting automobile navigation in urban scenarios. This method has successfully reduced 50% of the required map data. Joel C. McCall and Mohan M. Trivedi have proposed the video-based lane estimation and tracking (VioLET) to warn the drivers of departures [25]. In [26], the authors employ radio-frequency identification (RFID)-based vehicle positioning to facilitate connected vehicle applications at critical locations where GPS service is unavailable or unreliable. When a vehicle passes over an RFID tag, the vehicle position is given by the accurate position stored in the tag. While these traditional methods can enhance the accuracy in environment where the signal is not blocked, they are unable to provide the desired level of performance in certain environments where the signal is blocked.

With the advent of VANET, some researchers have begun to employ vehicular wireless communication to improve the positioning accuracy for VCPS applications [27]. Two architectures for VCPS applications have been proposed in [28,29] which integrate VANET and mobile cloud computing to improve the calculation power and storage capability using cloud servers. R. Parker and S. Valaee use the received-signal-strength indicator of a VANET node (vehicle or RSU) to realize vehicular positioning in [30]. In [31], authors proposed a GPS-free vehicular positioning framework by integrating Inertial Navigation Systems (INSs) and RSUs. This method discards the GPS receiver, uses a single RSU and INS instead to provide lane-level localization accuracy. However, the GPS receiver is gradually becoming a common component in vehicles, and discarding the GPS receiver will become an obstacle when it is large scale deployed. Vehicular cooperative localization has been discussed in [32] among VANET by using DSRC. This method poses a novel idea for vehicular positioning, but does not employ a RSU as a base station, despite the fact that the RSU's reference position is usually more precise than that of the mobile vehicle. Meanwhile, a positioning method based on inter-vehicle distance measurements has been proposed to improve the accuracy of position estimation by using the available VANET and existing communication devices in [33]. This method assumes the vehicle can estimate its own position independently, and employs VANET to share the position information to adjacent vehicle. This method performs well except in underground parking lots, urban center districts or tunnels. In summary, it is evident that the existing positioning methods are unable to satisfy the requirements for VCPS applications in these covered environments. Although the OSS-TWR method was proposed to remedy imprecise positioning for certain special environments, the positioning accuracy is rapidly worsened by the influence of wireless network collisions. Thus it is imperative that the OSS-TWR is improved to help to alleviate the effect of network collisions.

3. Problem statement

The OSS-TWR algorithm, proposed in [21], can remedy imprecise vehicular positioning estimation in certain special environment, such as in tunnels, and urban centers with dense skyscrapers. OSS-TWR employs RSUs as the position reference base station, to measure the flight time of radio signals and calculate the distance between the vehicle and RSUs. Then, the vehicular position can be simply deduced via trilateral positioning. The kernel of OSS-TWR is that use additional one time communication (synchronization frame) to translate the RSU clock system to vehicle clock system based on Two Way Ranging (TWR), namely build a time-mapping relationship between both clock systems. Firstly, the OSS-TWR suppose the communication network has no collision, and let the synchronization time (t_{delayB}) equal frame process time t_{replyB}, namely $t_{delayB} = t_{replyB}$. Secondly, it builds