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Vehicular Ad Hoc Networks: A New Challenge for Localization-Based Systems ☆

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Abstract

A new kind of ad hoc network is hitting the streets: Vehicular Ad Hoc Networks (VANets). In these networks, vehicles communicate with each other and possibly with a roadside infrastructure to provide a long list of applications varying from transit safety to driver assistance and Internet access. In these networks, knowledge of the real-time position of nodes is an assumption made by most protocols, algorithms, and applications. This is a very reasonable assumption, since GPS receivers can be installed easily in vehicles, a number of which already comes with this technology. But as VANets advance into critical areas and become more dependent on localization systems, GPS is starting to show some undesired problems such as not always being available or not being robust enough for some applications. For this reason, a number of other localization techniques such as Dead Reckoning, Cellular Localization, and Image/Video Localization has been used in VANets to overcome GPS limitations. A common procedure in all these cases is to use Data Fusion techniques to compute the accurate position of vehicles, creating a new paradigm for localization in which several known localization techniques are combined into a single solution that is more robust and precise than the individual approaches. In this paper, we further discuss this subject by studying and analyzing the localization requirements of the main VANet applications. We then survey each of the localization techniques that can be used to localize vehicles and, finally, examine how these localization techniques can be combined using Data Fusion techniques to provide the robust localization system required by most critical safety applications in VANets.

Keywords: Vehicular Networks; Localization; Data Fusion

1. Introduction

A number of interesting and desired applications of Intelligent Transportation Systems (ITS) have been stimulating the development of a new kind of ad hoc network: Vehicular Ad Hoc Networks (VANets) [1–5]. In these networks, vehicles are equipped with communication equipment that allows them to exchange messages with each other in Vehicle-to-Vehicle communication (V2V) and also to exchange messages with a roadside network infrastructure (Vehicle-to-Roadside Communication – V2R).

A number of applications are envisioned for these networks, some of which are already possible in some recently designed vehicles (Fig. 1):

- vehicle collision warning
- security distance warning
- driver assistance
- cooperative driving
- cooperative cruise control

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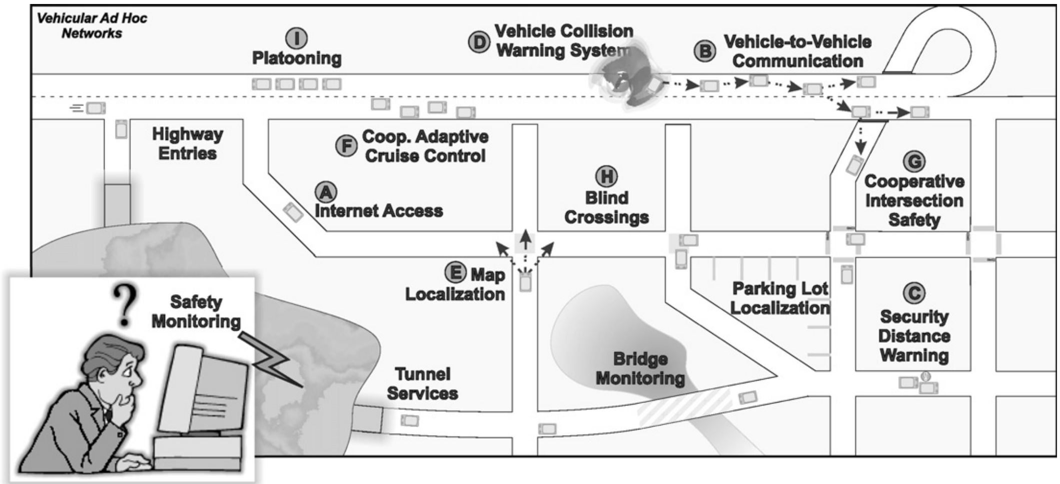

Fig. 1. Several VANet applications.

- dissemination of road information
- Internet access
- map location
- automatic parking
- driverless vehicles

All of these applications require, or can take advantage of, some sort of localization technique [6–11]. In the localization problem, the definition of a reference system among nodes is performed by identifying their physical location (e.g., latitude, longitude, and altitude) or their relative spatial distribution in relation to each other. For instance, Map Location is usually done using Global Positioning System (GPS) receivers with a Geographic Information System, while Vehicle Collision Warning Systems can be implemented by comparing distances between nodes' locations combined with geographic information dissemination.

As ITS and VANets technology advances toward more critical applications such as Vehicle Collision Warning Systems (CWS) and Driverless Vehicles, it is likely that a robust and highly available localization system will be required. Unfortunately, GPS receivers are not the best solution in these cases, since their accuracy range from up to 20 or 30 m and since they cannot work in indoor or dense urban areas where there is no direct visibility to satellites. For these reasons and, of course, for security reasons, GPS information is likely to be combined with other localization techniques such as Dead Reckoning, Cellular Localization, and Image/Video Localization, to cite a few. This combination of localization information from different sources can be done using such Data Fusion techniques as Kalman Filter and Particle Filter.

In this paper, we discuss the localization requirements of a number of VANet applications. We then survey several proposed localization techniques that can be used to estimate the position of a vehicle, and we highlight their advantages and disadvantages when applied to VANets. By concluding that none of these techniques can achieve individually the desired localization requirements of critical VANet applications, we show how the localization information from multiple sources can be combined to produce a single position that is more accurate and robust by using Data Fusion techniques.

The remainder of this paper is organized as follows. In the next section, we identify the location information requirements of several VANet applications, while in Section 3 we show how these positions can be computed through several localization techniques. Finally, Section 4 shows how Data Fusion techniques can be used to combine the position information gathered from these multiple sources. Section 5 provides our conclusions and future directions for localization systems in VANets.

2. Location-aware VANet applications

Most VANet applications consider the availability of real-time updated position information. They differ, however, on the localization accuracy required in order to be able to function properly. For instance, some applications can work with inaccurate localization information in which computed positions can have errors from 10 to 20 or 30 m, while other applications, especially critical safety applications, require more accurate and reliable localization systems with sub-meter precision. In this section, we divide VANet applications into three main groups according to their localization requirements and show how position information is used by these protocols and algorithms. These localization requirements for VANet applications are then summarized in Table 1.

2.1. Applications able to work with inaccurate localization

Although some VANet applications do not require any localization to function, most of them can take advantage of localization and show better performance when the posi-

Table 1
Required localization accuracy for some VANet applications

Technique	Localization Accuracy		
	Low	Medium	High
Routing	X	–	–
Data Dissemination	X	–	–
Map Localization	X	–	–
Coop. Adapt. Cruise Control	–	X	–
Coop. Intersection Safety	–	X	–
Blind Crossing	–	X	–
Platooning	–	X	–
Vehicle Col. Warn. System	–	–	X
Vision Enhancement	–	–	X
Automatic Parking	–	–	X

tion information of vehicles is available. Most of these applications are related to vehicle communication, which includes vehicle-to-vehicle (V2V) and vehicle-to-roadside (V2R) communication, and provide services such as information routing, and the data dissemination of accidents, road congestion, etc. The algorithms that deal with communication will accept localization errors mostly within 10–20 or even 30 m, since the long transmission range of the vehicles' transmitters can compensate for these localization inaccuracies. However, the greater the localization error, the worse the algorithms' performance [12]. In the following paragraphs we will discuss some of these applications and algorithms.

Routing protocols for VANets [13] usually use position information in order to improve their performance and be able to comply with such VANets requirements as dynamic topology changes and frequent network fragmentation. This routing technique has long been used in Ad Hoc networks [14–16] and most of its protocols can also be applied to VANets. A classical example is Greedy Forwarding [15,16], in which, location information is used at each step to forward a packet to the neighbor nearest to the destination node. However, some geographic routing protocols have also been designed specifically for VANets, taking advantage of more geographical knowledge such as Maps [17,18] and movement information [19]. Routing techniques are also used to access local infrastructured networks via an Internet connection (Fig. 1A). In these cases, position information as well as future trajectory knowledge can be used to assist routing.

Several *Data Dissemination* protocols [20,21] have been proposed for VANets that aim to inform both near and distant vehicles about transit conditions such as the road flow, congestion, and potentially dangerous situations. Most of these protocols also consider localization knowledge mostly to ensure that locally disseminated information reaches only the vehicles that should be interested in it. Driver direction can also be used, as proposed by the ODAM algorithm [21]. In Fig. 1B, road information about a dangerous situation is disseminated to interested vehicles.

A widely known and already in-use driver assistance application is *Map Localization*, in which the current position of the vehicle is shown on a map. In these applications, a path direction between two points of the city, for instance, can be drawn on a map indicating the current location of the vehicle. This application can assist drivers in situations when they find themselves lost in a unknown part of the city, as depicted in Fig. 1E. Localization information with errors of about 10–20 m are proven to be useful for this kind of application, since map knowledge can be used to overcome this high localization inaccuracy.

2.2. Applications requiring accurate localization

This kind of application require a certain degree of confiability and accuracy in the computed positions and/or in the distance estimation between vehicles. Applications in this group are usually Cooperative Driving applications, where vehicles in a VANet exchange messages between them to drive and share the available space on the road cooperatively. In these applications, the vehicles can assume partial control over driving. In most cases, localization errors from 1 to 5 meters are acceptable. In the following paragraphs we will discuss some of these applications and algorithms.

In *Cooperative Adaptive Cruise Control*, the vehicle maintains the same speed whether traveling uphill or down without requiring driver intervention. Usually, the driver sets the speed and the system will take over, but in this case, vehicles can cooperate among themselves to set this speed adaptively (Fig. 1F). This application only takes care of speed, while the driver still has to control the direction of the vehicle.

Another interesting application of VANets is *Cooperative Intersection Safety*, in which vehicles arriving at a road intersection exchange messages in order to make a safe crossing as depicted in Fig. 1G. Besides ensuring a safe crossing, it is also possible to make a *Blind Crossing*, where there is no light control and the vehicles cooperate with each other to make a cooperative crossing (Fig. 1H). In these applications, the localization accuracy must allow the application to differentiate between the lanes as well as the sides of the street.

Vehicle Following or *Platooning* is a technique used to make one or more vehicles follow a leader vehicle to form a train-like system, as shown in Fig. 1I. This application can be useful in situations where two or more vehicles are going to the same location. A minimum distance must be ensured between vehicles. Also, vehicles must track the position of the vehicle in front of them with a good precision, both of which can be accomplished by a localization system with accurate position information.

2.3. Applications requiring high-accurate localization

A third class of applications for VANets requires very precise and reliable localization systems. Most of these applications are critical safety applications such as Vehicle Collision Warning Systems (CWS) and other driver assistance applications. In driver assistance applications, VANet resources are used to enhance the driver's perception and knowledge of the road and environment. In these

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applications, the driver is informed about the surrounding environment in order to improve safety, and, in case of emergency, the vehicle can perform some automatic procedures. These are the most interesting applications for VANets, and since we are dealing with safety, position information reliability and accuracy are crucial. Accurate positioning ensures localization with a meter or sub-meter precision in order to estimate accurately the distances between vehicles, while a reliable localization will ensure that updated information will always be available. In the following paragraphs we will discuss some of these applications and algorithms.

Vehicle Collision Warning Systems [1,21] are one of the most interesting applications of VANets for driver assistance. One part of these systems is *Security Distance Warning*, in which the driver is warned when a minimum distance to another vehicle is reached (Fig. 1C). It can also implement an emergency break when the distance between two vehicles or between a vehicle and an obstacle decreases too quickly, as shown in Fig. 1D. Another part of these systems is when a collision has already occurred and nearby vehicles need to be warned (warn messages) so they can avoid pile-up collisions (Fig. 1D). In these cases, multihop communication can be used to disseminate collision information. Since they provide a critical application for safe driving, these applications require robust, accurate, and reliable localization systems.

Another driver assistance application is *Vision Enhancement*, in which drivers are given a clear view of vehicles and obstacles in heavy fog conditions and can learn about the existence of vehicles hidden by obstacles, buildings, and by other vehicles.

Automatic Parking is an application through which a vehicle can park itself without the need for driver intervention. In order to be able to perform an automatic parking, a vehicle needs accurate distance estimators and/or a localization system with sub-meter precision.

3. Localization techniques for Vehicular Ad Hoc Networks

A number of localization techniques has been proposed for computing the position of mobile nodes. An interesting aspect of VANets is that most localization techniques can be applied easily to these networks. Fig. 2 depicts a number of localization techniques that can be used by vehicles to estimate their positions, namely Map Matching, Dead Reckoning, Cellular Localization, Image/Video Processing, Localization Services, and Relative Distributed Ad Hoc Localization. All of these techniques have their pros and cons. In this section we briefly explain each of these techniques and discuss when and how they can be used to localize vehicles in Intelligent Transport Systems.

3.1. Global Positioning System – GPS/DGPS

GPS, the Global Positioning System [22,23], is composed of 24 satellites that operate in orbit around the earth.

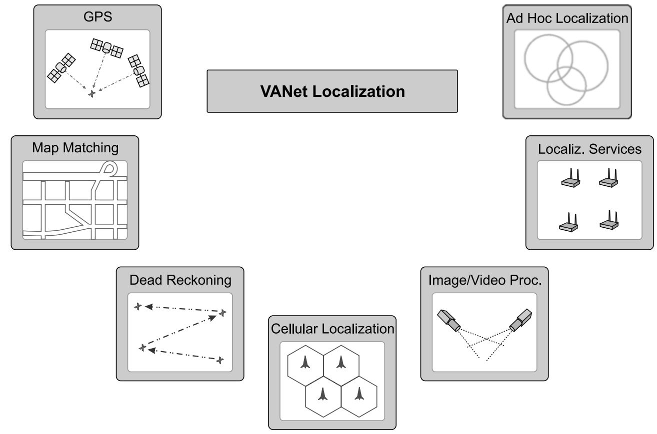

Fig. 2. Several localization techniques for VANet.

Each satellite circles the earth at a height of 20.200 km and makes two complete rotations every day. The orbits have been defined in such a way that each region of the earth can "see" at least four satellites in the sky.

A GPS receiver is a piece of equipment that is able to receive the information constantly being sent by the satellites, and uses this information to estimate its distance to at least four known satellites using a technique called Time of Arrival (ToA), and, finally, to compute its position using trilateration [10]. Once these procedures have been executed, the receiver is able to know its latitude, longitude and altitude.

The main solution for VANet Localization is to equip each vehicle node with a GPS receiver (Fig. 3A). This is a very reasonable solution since GPS receivers can be installed easily in vehicles, a number of which already comes with this technology. But as VANets advance into critical areas and become more dependent on localization systems, GPS, as well as other satellite-based positioning systems (e.g., Galileo, GLONASS), are starting to show some undesired problems such as not always being available and not being robust enough for critical applications.

In order to function properly and compute its position, a GPS receiver needs access to at least three satellite signals for 2D positioning and at least four satellite signals for a 3D position computation. At first sight, this is not a major issue since the number of visible satellites usually varies between four and eleven. However, the problem is that these signals are easily disturbed or blocked by obstacles including buildings, rocks, dense foliage, electronic interference, etc. This causes position inaccuracy or unavailability in dense urban environments (urban-canyons), tunnels, indoor parking lots, forests, and any other indoor, underground, or underwater environment.

Also, GPS receivers have a localization error of ±10 to 30 m. While this is a reasonable level of precision for most applications, it is definitely not enough for critical VANet applications, as explained in Section 2. One positive aspect of these errors is that nearby GPS receivers tend to have the same localization error pointing in the same direction. In other words, nearby GPS receivers have correlated

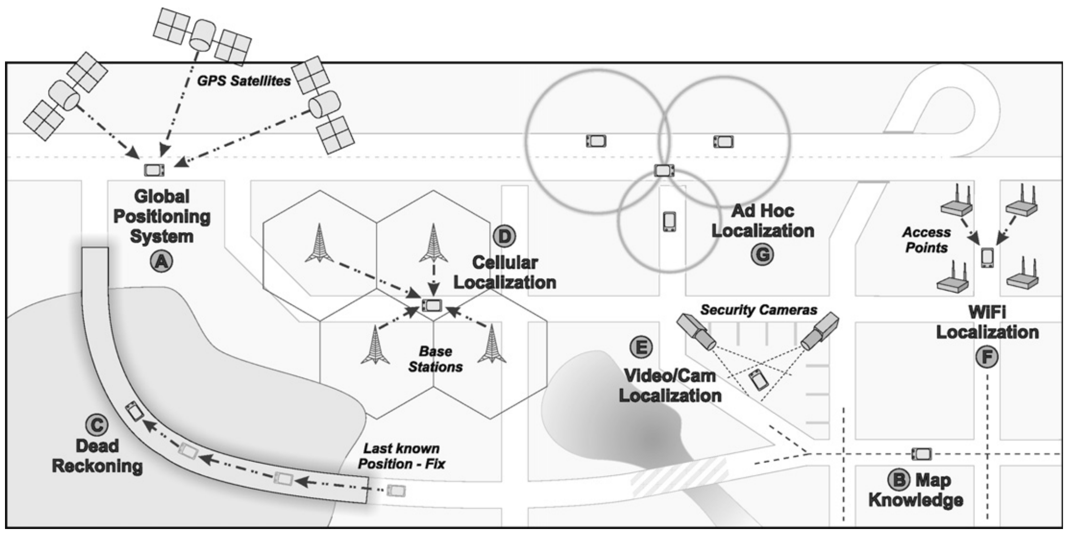

Fig. 3. Examples of localization techniques applied in VANets.

errors. Differential GPS (DGPS) takes advantage of these correlated errors by installing a GPS receiver in an already known fixed location. This GPS receiver can compute its position using the information from the satellites and compare the computed position with its already known physical location. The difference between these two positions can be broadcasted and all nearby GPS receivers can correct their computed positions based on the broadcasted differential information. This is why this technique is known as Differential GPS. A drawback of this technique is that fixed ground-based reference stations must be used to broadcast this differential information. On the other hand, DGPS can lead to a sub-meter precision, which is sufficient for most VANet critical applications. Another advantage of the correlated errors obtained by normal GPS receivers is that relative distances between receivers can be accurately estimated even though the computed positions are not accurate.

Due to the cited limitations, normal GPS receivers are usually used only in VANet applications that do not require accurate and reliable information, such as the applications studied in Section 2.1. When combined with geographic knowledge [24,25], as will be explained in the next section, GPS can also be used in applications that require greater accuracy (Section 2.2). At last, in order to be used by critical applications, position information obtained via GPS needs to be combined with different sources of position information, differential information, and/or geographic knowledge. In the next sections we will show most of these techniques that can be used as sources of position information to improve GPS localization or to completely replace it in locations where GPS is not available.

3.2. Map matching

Current advances in Geographic Information Systems (GIS) have allowed the collection and storage of, as well as access to, very accurate geographic data even for less powerful devices. This technology has been successfully applied to store city map information in recently developed map localization systems for vehicle navigation (as in Fig. 3B).

Aside from the fact that this map knowledge is not a localization technique by itself, it can be used to improve the performance of many positioning systems such as GPS. First, by limiting the estimated vehicle positions to roads or other places with vehicle access, it is possible to decrease the error of the estimated positions. But the main application of map knowledge in localization is the Map Matching technique [24,25].

In the Map Matching technique, several positions obtained over regular periods of time can be used to create an estimated trajectory. This estimated trajectory is then compared to known digital map data to find the most suitable path geometry on the map that matches the trajectory. Using this technique, position information (e.g., from GPS) can be accurately depicted on the map.

3.3. Dead reckoning

By using Dead Reckoning [19,25], the current position of a vehicle can be computed based on its last known location and using such movement information as direction, speed, acceleration, distance, time, etc. The last known position, also known as a fix, can be obtained, for instance, by using GPS receivers (which are most common) or by locating a known reference (road crossing, parking lots, home, etc) on a digital map. Displacement information can be obtained by sensors including odometers, while direction can be estimated easily using such other sensors as digital compasses and gyroscopes.

In practical VANets, Dead Reckoning can be used only for short periods of GPS unavailability, or be combined with Map Knowledge. The reason to avoid the use of this

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technique over long periods of time is that it can accumulate errors easily. For instance, positioning errors from 10 to 20 m can be reached in only 30 s after the last position fix when traveling at about 100 km/h [7,26].

Since Dead Reckoning accumulates errors rapidly over time and distance, it is considered only as a backup system for periods of GPS outage, as shown in Fig. 3C, in which a vehicle enters a tunnel and loses its GPS connection. In this example, the last GPS computed position is used as a position fix. Another viable application of Dead Reckoning, as noted above, is to combine it with Map Knowledge. In these cases, the positions restrictions can be applied to decrease Dead Reckoning errors, and the traffic patterns can be used to match the estimated path within the known map information (map matching) [25].

3.4. Cellular localization

Cellular localization [27–30] takes advantage of the mobile cellular infrastructure present in most urban environments to estimate the position of an object. Known applications of this technology include locating mobile phones, tracking domestic animals, and vehicle localization.

In order to function properly, mobile cellular systems require the installation of a communication infrastructure composed of a number of cellular base stations distributed through the covered area. Each base station is responsible for providing communication to mobile phones located in its area. As mobile phones move around a city, they keep changing their base station when the signal strength from a new base station becomes greater than the one in use. This procedure is called handoff.

Although only one base station is used in communication, usually several base stations can listen to and communicate with a mobile phone at any time. This fact allows a number of localization techniques to be used to estimate the position of the mobile phone. A well known technique called Received Signal Strength Indicator (RSSI) uses the strength of the received signals to derive the distance to the base stations. It is also possible to estimate a distance based on the time it takes for a signal to leave the sender and arrive at the base station (Time of Arrival – ToA) or the difference between the times it takes for a single signal to arrive at multiple base stations (Time Difference of Arrival – TDoA). Once we have the distances from the mobile phone to at least three base stations, it is possible to compute the position of the mobile phone using such techniques as trilateration and multilateration [10] (Fig. 3D).

Another common approach is possible when directive antennas or antenna arrays are used at base stations. In this case, the angle at which the signal arrives at a base station can be estimated. Based on the Angle of Arrival (AoA) of a signal to three different base stations, we can compute the position of the signal source.

Fingerprinting is a localization technique based on a pre-training phase in which signal characteristics from base stations are recorded at each location. After this information is recorded, a mobile node can find the position in the database that best matches its current signal characteristics. This is a very interesting solution for small or medium sized areas, achieving errors of less than 5 m in indoor environments [29]. For large urban areas as in VANet applications it has questionable applicability, but in some recent studies [30], an average accuracy of 94 m is achieved after a 60-h calibration drive in a metropolitan area.

Cellular localization is usually less precise than GPS. The accuracy depends on a number of factors such as the current urban environment, the number of base stations detecting the signal, the positioning algorithm used, etc. In most cases, the average localization error will be between 90 m and 250 m [30], which is not accurate enough even for VANet applications that do not require accurate and reliable information such as the applications studied in Section 2.1. However, position information gathered from this technique can still be useful when combined with Dead Reckoning and/or Map Matching, and the available information can also be used to feed Data Fusion modules as will be explained in Section 4. Also, signals from the Cellular infrastructure have more availability in urban environments than signals from satellite (used by GPS receivers) which can be useful for indoor environments such as parking lots and even tunnels, especially if the fingerprinting technique explained above is used.

3.5. Image/video processing

Image and video information sources and data processing techniques can also be used for localization purposes, especially in mobile robot guidance systems [31]. In some cases, however, cameras are already available in security systems implemented in parking lots and tunnels, as shown in Fig. 3E. Commonly, these Image/Video Processing techniques are used to feed Data Fusion algorithms to estimate and predict (track) a vehicle's location [32]. In fact, both image and video information are actual sources from which we can compute the location parameters of a vehicle. For instance, in [33] vision algorithms [34] are used to detect the sides of lanes in video images. It estimates precisely the vehicle's geometrical parameters in a local reference system, including lane width, road lateral curvature, distance of the vehicle from the left side of the lane, vehicle's direction angle, and the camera inclination angle. These local data are transformed in order to be expressed in a precise digital map of the environment. Such information is used to feed a Data Fusion module that estimates the vehicles' locations. Data Fusion techniques for VANet localization will be discussed further in Section 4.

3.6. Localization services

There are places where GPS is not available or not precise enough for local applications. In VANets, as mentioned in Section 3.1, these places include tunnels, urban-canyons, and parking lots. In these cases, an infrastructure for communication and positioning service can be implemented to perform the localization of vehicles, as shown in Fig. 3F.

A Localization Service can be implemented using any known infrastructured localization system such as the Cricket Location-Support System [35], RADAR [36], Ultra-Wideband Localization [37], or WiFi Localization [38,39]. In [39], Thangavelu et al. propose a system called VETRAC, a vehicle tracking and location identification system designed for VANets that uses WiFi access points as a communication infrastructure and also as landmarks when positioning vehicles. The proposed system can be used in tunnels, university campuses, airports, etc.

In most cases, localization services are likely to take advantage of the communication system in use to compute a vehicle's position based on signal propagation characteristics (e.g., strength, time, or fingerprint). However, other indoor localization systems such as Image/Video Processing (explained in Section 3.5) or Laserscanners can also be used.

The most challenging and important task in VANet localization is most likely the development of infrastructured localization systems to be used in tunnels, which are one of the most critical VANet environments. Tunnels are normally used to connect important regions separated by natural environments with difficult access and are generally the only path between these regions. Thus, a damaged tunnel can have an enormous impact on a city or a region. Also, due to the limited access inside a tunnel, emergency rescue operations can become very difficult and even dangerous. In these scenarios, collision avoidance is crucial, and all available information about the state of these tunnels' infrastructure as well as the number and location of all vehicles inside these tunnels are key information for rescue teams in case of emergency operations.

VANets can also use Wireless Sensor Networks (WSNs) as the base for a VANet localization infrastructure. The reason for doing this is that WSNs can also be used to monitor other road variables like movement, temperature, smoke, visibility, and noise. Thus, these networks are ideal for monitoring critical environments as well as for emergency operations, as shown by a number of works [40,41]. Also, the use of sensor networks as a roadside communication infrastructure is a frequently envisioned scenario in many Intelligent Transportation Systems. A number of WSN features can also be used to improve the performance and accuracy of an infrastructured VANet localization system. For instance, movement sensors can be used to send localization packets only when vehicles are present. These sensors can also be used to increase the localization accuracy by making nodes exchange their sensors' movement detection level. Finally, a WSN used as a VANet localization infrastructure will provide a complete safety monitoring system for these critical scenarios, being able not only to monitor important environment and structural variables like movement, temperature, smoke, visibility, noise, pressure, and structural health, but also the location of all vehicle nodes at a given moment.

3.7. Relative distributed ad hoc localization

Local relative position maps can be constructed by a vehicle by estimating the distances between its neighbors and exchanging this distance information with nearby nodes in multihop communication. With this dynamic position map, a vehicle can locate itself in relation to nearby vehicles as well as locate the vehicles in its vicinity (Fig. 3G). This type of relative localization has been used mostly in Ad Hoc and Sensor Networks, but recently a number of solutions [6,7,26] has been proposed for VANets.

In [6], a distributed localization algorithm is proposed to assist GPS-unequipped vehicles in estimating their positions based on nearby GPS-equipped vehicles. To estimate a position, a vehicle not equipped with GPS needs to communicate with at least three GPS-equipped vehicles in its vicinity in order to estimate distances and gather their position information. When the number of nearby GPS-equipped vehicles is less than three, the author shows how to estimate at least the direction of the vehicle and the distance from an event (an accident or a danger) based on the small amount of available information. The proposed algorithm can successfully estimate the position of vehicles not equipped with GPS, but it is hard to identify situations where vehicles have network cards to communicate with other vehicles but have no GPS equipment. Also, the direction of the cars can be easily estimated by exchanging digital compass or gyroscopes information.

In [7], another distributed VANet localization system is proposed in which distances between vehicles are estimated using RSSI and the information is used by an optimization algorithm to improve the initial position estimation of the vehicles (obtained, for instance, via GPS). This technique is primarily intended to improve GPS's initial position estimations, but since nearby GPS receivers tend to have correlated errors, estimating distances using RSSI will hardly improve the position information. However, this solution can also be used to improve positions computed via the Dead Reckoning technique during GPS outages.

A number of distributed relative ad hoc localization systems have been proposed recently for Ad Hoc and Sensor networks [42,43], but only a few of these can be applied to highly mobile and dynamic networks such as VANets. In [26], Kukshya et al. propose an architecture for the relative positioning of a cluster of vehicles that does not require any GPS information and that is suitable for VANets. This architecture also relies on distance estimation measurements.

Most VANet applications can work with relative positioning, but they would function better using global posi-

Table 2
Localization techniques: a comparison

Technique	Localization feature			
	Synchroniz.	Infrastruct.	Availability	Accuracy
Global Pos. System	Yes	Yes	No	No
Differential GPS	Yes	Yes	No	Yes
Map Matching	No	No	Yes	No
Dead Reckoning	No	No	Yes	No
Cellular Loc.	Yes	Yes	No	No
Img/Video Loc.	No	Yes	No	Yes
Loc. Services	No	Yes	No	Yes
Rel. Ad Hoc Loc.	No	No	Yes	Yes

tioning. In these cases, relative positions can usually be converted into global positions when some vehicles with GPS or accurate global positions are available, as done in [7,6].

3.8. Techniques comparison

All of these localization techniques studied have their pros and cons. Table 2 briefly compares these techniques. As we can see from the table, although several interesting solutions have been reported in the literature, basically none of them satisfy all the requirements of critical applications at the same time, such as being available anywhere and anytime, with highly accurate and reliable position computations. For these reasons, one of the most appealing problems to be solved by VANets is how to provide an anytime, anywhere, fine-grained, and reliable localization system to be used by vehicles in a VANet for critical safety and emergency applications. An *anytime* requirement means that the localization system must be free of delays when computing the current positions of the vehicles (e.g., no startup delay). This requirement is critical, since the high mobility of VANets means that slightly outdated position information cannot be used and could even be dangerous. To be available *anywhere* is also a challenge in a VANet localization system. It means that the localization system cannot rely only on satellite infrastructure, since it would then not work in environments without direct visibility to satellites. Also, it cannot rely only on local infrastructured localization techniques, since it would not be available in places without this infrastructure. Finally, a *fine-grained* localization system ensures a low localization error for vehicles, which enables most critical VANet applications to have some degree of confidence.

As shown in Table 2, it is clear that a single technique will not be enough to provide a localization system with all of the features requested by critical VANet applications. As a result, ways to combine different localization techniques and protocols in a single localization system will be required. Data-fusion techniques, which will be studied in the next section, are the natural choice for technique combinations aimed at acquiring improved data [32].

4. Data Fusion in VANets' localization systems

Data Fusion can be simply defined as the combination of multiple sources to obtain improved information (cheaper, greater quality, or greater relevance) [32]. Data Fusion is commonly used in detection and classification tasks in different application domains, such as robotics and military applications [44]. Lately, these mechanisms have been used in previously unpredicted applications such as intrusion detection [45] and Denial of Service (DoS) detection [46]. Within the domain of WSNs, simple aggregation techniques (e.g., *maximum*, *minimum*, and *average*) have been used to reduce the overall data traffic to save energy [47]. A detailed description of data-fusion techniques is not the focus of this paper, however. Further details about these techniques are described in [32].

4.1. A possible Data Fusion model

Data Fusion techniques such as Kalman Filters, Particle filters, and Belief Theory have also been used to improve location estimations in many sensor-based systems [32]. For instance, the SAFESPOT [48] approach for the accurate relative positioning of vehicles foresees the use of Data Fusion to help with accurate position estimation in VANets. The key idea is to combine information from a cooperative vehicle ad hoc network using a Data Fusion module to allow vehicular safety applications to determine not only a vehicle's location, but also the lane in which it is traveling. The general idea behind a location system based on Data Fusion is to combine several information sources to provide an accurate location estimation.

Theoretically, data-fusion techniques may be used in almost every stage of a location estimation process for VANets. As an example, Fig. 4 depicts a possible data-fusion model that can be applied to acquire accurate position estimations. This model has the following components:

- *Range sources:* There are several possible data sources that can provide distance estimations, such as ultrasound, laser, RSSI, ToA, and TDoA. Such range sources may be deployed on the road, in vehicles, and on nearby buildings.
- *Range fusion:* Every range source may embed some level of noise. In this context, all available distance estimations can be fused (filtered) to reduce the embedded noise. Data-fusion estimation methods – such as moving average, Kalman, and particle filters [32] – are suitable for this component.
- *Range-based estimation:* Once we have a fused distance estimation, we can use such information to compute the vehicle's position by using, for instance, a multilateration process.
- *Range-free estimation:* Occasionally, a range free localization system may be used as side information to complement the other position estimations available.

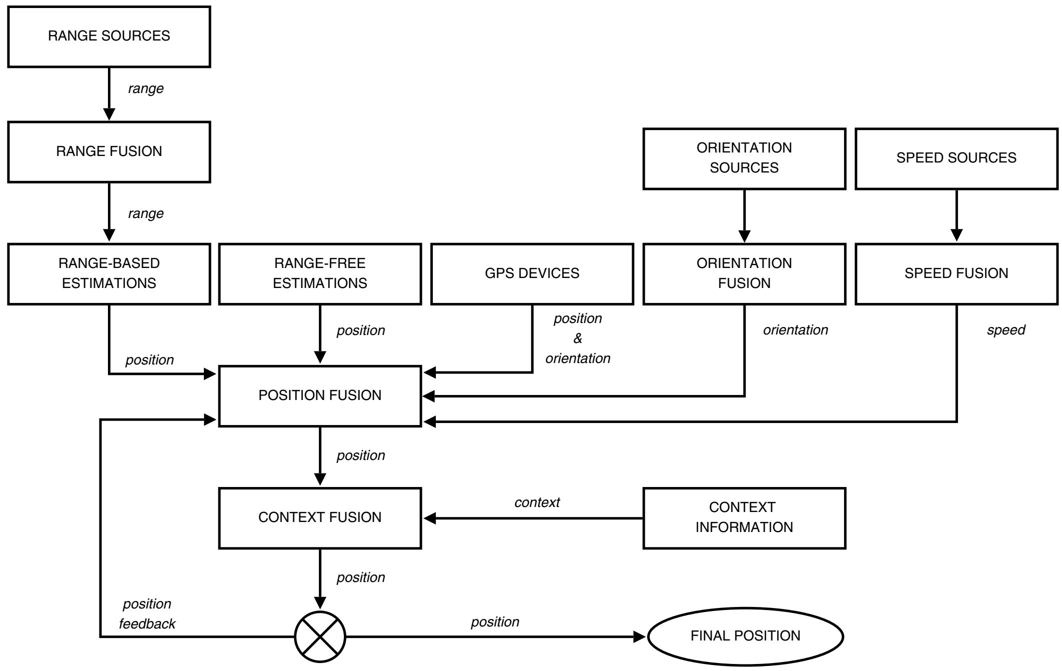

Fig. 4. Possible data-fusion model for node localization in VANets.

- *GPS devices:* In VANets it is reasonable to assume that several vehicles are equipped with GPS because the associated cost is reduced compared to the overall cost of a vehicle. Thus, these devices can be used to provide position information (and orientation) whenever possible (i.e. satellites must be reachable).
- *Orientation sources:* Such sources inform the direction of movement and orientation of a vehicle. They can be estimated by collecting neighborhood information (i.e. other vehicles or landmarks along the roads).
- *Orientation fusion:* When several orientation sources are available, they can be refined by using a fusion technique. Again, estimation methods such as moving average, least squares, Kalman, and particle filters [32] are suitable for this component.
- *Speed sources:* Potential speed sources are the vehicles' odometers (including a neighbor vehicle) and road odometers (used, for instance, to check whether or not a vehicle respects the speed limit).
- *Speed fusion:* Again, data-fusion can be applied to increase the speed estimation when multiple sources are available. For speed fusion, estimation methods – such as Kalman, least squares, and particle filters [32] – are suitable for this component as well.
- *Position fusion:* This is a key element. In VANets, the localization problem incorporates the tracking problem since vehicles are usually moving and, depending on the movement speed, a simple position estimation (without prediction) may be instantly out-of-date. Thus, this component is responsible for fusing position estimations, speed, and orientation information to predict where the vehicle is headed. In addition, this component can fuse position estimations provided by multiple localization systems. For instance, if the vehicle (or someone inside the vehicle) is using a WiMAX and/or a cellular network, we can use a localization solution to estimate the position of the WiMAX node and the cellular node and fuse these with the vehicle position estimation. Again, estimation methods such as least squares, moving average, Kalman, and particle filters [32] are suitable for this component.
- *Context fusion:* Context information can be fused with position estimations to improve accuracy. To illustrate the use of context information, consider the following examples:
  - When a map is available, if the estimated position is not within the street borders and we have evidence that the vehicle remains on the street, then we can correct that position estimation.
  - When we have information about traffic jams, a predicted position of a car (that is moving fast) can be corrected to reflect a traffic jam in which the car will get stuck.
  - When the itinerary is known, we can correct a predicted position to reflect orientation changes (e.g. curves) that could not be predicted otherwise.

For context fusion, inference methods such as Bayesian inference, Dempster-Shafer, Fuzzy Logic, and Neural Networks [32] can be used to combine position estimations and context information.

- *Final position:* Once it is known, the correct position should feedback the *Position Fusion* component to allow more accurate estimations.

4.2. Current approaches

In the specific context of emerging VANets, the potential of data-fusion has not been properly explored. Considering the fusion model depicted in Fig. 4, current solutions use data-fusion to predict where the vehicle is moving – which partially corresponds to the *Position Fusion* component – and use some context information to improve accuracy – which partially corresponds to the *Context Fusion* component.

In [49], the authors use Particle Filters to cope with vehicle localization in combined indoor and outdoor scenarios. In such scenarios, the authors assess the performance of UWB sensor technology for indoor positioning and GPS for outdoor areas, and evaluate the use of particle filters to fuse observations from these two types of sensors for vehicle localization. Particle Filters are also used in [33] to combine GPS localization with data extracted from vision systems to determine a vehicle's location on the road. The combined information is transformed into a global reference using a map of the environment.

In the context of vehicle localization for production and logistic applications, [50] applies Kalman filters to track the position of all transportation means when picking up or putting down items by combining a wireless local positioning system with an optical scan match approach.

Aiming at improving security on the roads, [51] uses a Kalman filter for trajectory prediction and the estimation of a vehicle's location to evaluate and anticipate the risk of collision at a crossroad. The authors show that despite unavoidable latencies and positioning errors, the application performance is still acceptable when a Kalman filter is used for trajectory prediction and estimation.

In [52], Belief Theory and Kalman filters are used to provide accurate position estimations for a vehicle relative to a digital road map. In this method, the Kalman Filter is used to combine the Anti-lock Braking Systems (ABS) measurements with a GPS position, which is then used to select the most credible roads. The selection strategy fuses distance, direction, and velocity measurements using Belief Theory. A new observation is then built and the vehicle's approximate location is adjusted by a second Kalman filter.

Table 3
Summary of current data fusion solutions for Localization in VANets

Solution	Fusion Type				
	Range	Orient.	Speed	Pos.	Context
Chausse et al. [33]	No	No	No	Yes	Yes
Fernandez-Madrigal et al. [49]	No	No	No	Yes	Yes
Michel et al. [50]	No	Yes	No	Yes	Yes
Ammoun et al. [51]	No	No	No	Yes	Yes
Najjar and Bonnifait [52]	No	No	No	Yes	Yes

Note that none of these solutions exploits all of the fusion components depicted in Fig. 4. Most of them exploit some level of context information. However, depending on the application, other context information should be used, such as itinerary and traffic information. In general, *Range Fusion*, *Orientation Fusion*, and *Speed Fusion* are neglected by current solutions. Table 3 summarizes how current solutions fit within the data-fusion model depicted in Fig. 4.

5. Conclusions

In this paper, Localization Systems were studied from the viewpoint of Vehicular Ad Hoc Networks (VANets). We showed how GPS receivers, the most common source of localization information in VANets, can become erroneous or unavailable in a number of situations. We then discussed how these localization inaccuracies can affect most VANet applications, especially critical ones. A number of other localization systems are available to be used by vehicles to estimate their positions: Map Matching, Dead Reckoning, Cellular Localization, Image/Video Processing, Localization Services, and Relative Distributed Ad Hoc Localization. All of these techniques have their pros and cons. In this paper we argue that future localization systems for VANets are likely to use some kind of Data Fusion technique in order to provide position information for vehicles that is accurate and robust enough to be applied in VANet critical applications. We then show how Data Fusion techniques can be used to compute an accurate position based on a number of relatively inaccurate position estimations.

References

[1] S. Biswas, R. Tatchikou, F. Dion, Vehicle-to-vehicle wireless communication protocols for enhancing highway traffic safety, IEEE Communications Magazine 44 (1) (2006) 74–82.
[2] J. Blum, A. Eskandarian, L. Hoffman, Challenges of inter-vehicle ad hoc networks, IEEE Transactions on Intelligent Transportation Systems 5 (4) (2004) 347–351.
[3] W. Kiess, J. Rybicki, M. Mauve, On the nature of inter-vehicle communication, in: WMAN 2007: Proceedings of the 4th Workshop on Mobile Ad-Hoc Networks, 2007, pp. 493–502.
[4] J. Luo, J.-P. Hubaux, A survey of inter-vehicle communication, Tech. Rep. IC/2004/24, School of computer and Communication Sciences, EPEL, 2004.
[5] J. Hubaux, S. Capkun, J. Luo, The security and privacy of smart vehicles, IEEE Security and Privacy Magazine 02 (3) (2004) 49–55.
[6] A. Benslimane, Localization in Vehicular Ad Hoc Networks, in: Proceedings Systems Communications, 2005, pp. 19–25.
[7] R. Parker, S. Valaee, Vehicle localization in Vehicular Networks, in: Vehicular Technology Conference, 2006. VTC-2006 Fall. 2006 IEEE 64th, 2006, pp. 1–5.
[8] V. Zeimpekis, G.M. Giaglis, G. Lekakos, A taxonomy of indoor and outdoor positioning techniques for mobile location services, SIGecom Exchange 3 (4) (2003) 19–27, URL http://portal.acm.org/citation.cfm?id=844355 .
[9] F. Gustafsson, F. Gunnarsson, Mobile positioning using wireless networks: possibilities and fundamental limitations based on avail-

able wireless network measurements, IEEE Signal Processing Magazine 22 (4) (2005) 41–53.
[10] A. Boukerche, H.A.B.F. Oliveira, E.F. Nakamura, A.A. Loureiro, Localization systems for wireless sensor networks, IEEE Wireless Communications – Special Issue on Wireless Sensor Networks vol. 14, 2007, pp. 6–12.
[11] H.A.B.F. Oliveira, E.F. Nakamura, A.A. Loureiro, A. Boukerche, Localization in time and space for sensor networks, in: AINA'07: 21st IEEE International Conference on Advanced Information Networking and Applications, Niagara Falls, Canada, 2007, pp. 539–546.
[12] R. Shah, A. Wolisz, J. Rabaey, On the performance of geographical routing in the presence of localization errors [ad hoc network applications], in: IEEE International Conference on Communications, ICC 2005, vol. 5, 2005, pp. 2979–2985.
[13] J. Chennikara-Varghese, W. Chen, O. Altintas, S. Cai, Survey of routing protocols for inter-vehicle communications, in: 3rd Annual International Conference on Mobile and Ubiquitous Systems - Workshops, 2006, pp. 1–5.
[14] Y.-B. Ko, N.H. Vaidya, Location-aided routing (LAR) in mobile ad hoc networks, in: Mobile Computing and Networking, 1998, pp. 66–75.
[15] B. Karp, H.T. Kung, Gpsr: Greedy perimeter stateless routing for wireless networks, in: 6th International Conference on Mobile Computing and Networking, Boston, MA, USA, 2000, pp. 243–254.
[16] Y. Yu, R. Govindan, D. Estrin, Geographical and energy aware routing: A recursive data dissemination protocol for wireless sensor networks, Tech. Rep. CSD-TR-01-0023, UCLA Computer Science Department, 2001.
[17] J. Tian, L. Han, K. Rothermel, Spatially aware packet routing for mobile ad hoc inter-vehicle radio networks, in: ITS'03: IEEE Intelligent Transportation Systems, vol. 2, 2003, pp. 1546–1551.
[18] C. Lochert, H. Hartenstein, J. Tian, H. Fussler, D. Hermann, M. Mauve, A routing strategy for Vehicular Ad Hoc Networks in city environments, in: IVS'03: IEEE Intelligent Vehicles Symposium, 2003, pp. 156–161.
[19] T. King, H. Füßler, M. Transier, W. Effelsberg, Dead-reckoning for position-based forwarding on highways, in: Proceedings of the 3rd International Workshop on Intelligent Transportation (WIT 2006), Hamburg, Germany, 2006, pp. 199–204.
[20] M.-T. Sun, W.-C. Feng, T.-H. Lai, K. Yamada, H. Okada, K. Fujimura, Gps-based message broadcast for adaptive inter-vehicle communications, in: Vehicular Technology Conference, 2000. IEEE VTS-Fall VTC 2000. 52nd, vol. 6, 2000, pp. 2685–2692.
[21] A. Benslimane, Optimized dissemination of alarm messages in Vehicular Ad Hoc Networks (VANets), in: HSNMC, 2004, pp. 655–666.
[22] B. Hofmann-Wellenho, H. Lichtenegger, J. Collins, Global Positioning System: Theory and Practice, 4th ed., Springer-Verlag, 1997.
[23] E.D. Kaplan, Understanding GPS: Principles and Applications, Artech House, 1996.
[24] G.R. Jagadeesh, T. Srikanthan, X.D. Zhang, A map matching method for gps based real-time vehicle location, Journal of Navigation 57 (2005) 429–440.
[25] E. Krakiwsky, C. Harris, R. Wong, A kalman filter for integrating dead reckoning, map matching and gps positioning, in: Position Location and Navigation Symposium, 1988. Record. 'Navigation into the 21st Century'. IEEE PLANS'88., IEEE, 1988, pp. 39–46.
[26] V. Kukshya, H. Krishnan, C. Kellum, Design of a system solution for relative positioning of vehicles using vehicle-to-vehicle radio communications during gps outages, in: Vehicular Technology Conference, 2005. VTC-2005-Fall. 2005 IEEE 62nd, Vol. 2, 2005, pp. 1313–1317.
[27] H.-L. Song, Automatic vehicle location in cellular communications systems, IEEE Transactions on Vehicular Technology 43 (4) (1994) 902–908.
[28] J. Caffery, G. Stuber, Overview of radiolocation in cdma cellular systems, IEEE Communications Magazine 36 (4) (1998) 38–45.
[29] A. Varshavsky, M.Y. Chen, E. de Lara, J. Froehlich, D. Haehnel, J. Hightower, A. LaMarca, F. Potter, T. Sohn, K. Tang, I. Smith, Are gsm phones the solution for localization? in: Mobile Computing Systems and Applications, 2006. WMCSA'06. Proceedings of 7th IEEE Workshop on, 2006, pp. 20–28.
[30] M. Chen, D. Haehnel, J. Hightower, T. Sohn, A. LaMarca, I. Smith, D. Chmelev, J. Hughes, F. Potter, Practical metropolitan-scale positioning for gsm phones, in: Proceedings of 8th Ubicomp, Orange County, California, 2006, pp. 225–242.
[31] T. Schmitt, R. Hanek, M. Beetz, S. Buck, B. Radig, Cooperative probabilistic state estimation for vision-based autonomous mobile robots, IEEE Transactions on Robotics and Automation 18 (5) (2002) 670–684.
[32] E.F. Nakamura, A.A. Loureiro, A.C. Frery, Information fusion for wireless sensor networks: Methods, models, and classifications, ACM Computing Surveys 39 (3) (2007) 55.
[33] F. Chausse, J. Laneurit, R. Chapuis, Vehicle localization on a digital map using particles filtering, in: Intelligent Vehicles Symposium, 2005. Proceedings of IEEE, 2005, pp. 243–248.
[34] R. Chapuis, J. Laneurit, R. Aufrere, F. Chausse, T. Chateau, Accurate vision based road tracker, Intelligent Vehicle Symposium, 2002, vol. 2, IEEE, 2002, pp. 666–671.
[35] N.B. Priyantha, A. Chakraborty, H. Balakrishnan, The cricket location-support system, in: Mobile Computing and Networking, Boston, MA, USA, 2000, pp. 32–43.
[36] P. Bahl, V.N. Padmanabhan, Radar: An in-building rf-based user location and tracking system, Proceedings of the IEEE Infocom 2000, vol. 2, IEEE, Tel Aviv, Israel, 2000, pp. 775–784.
[37] J.-Y. Lee, R. Scholtz, Ranging in a dense multipath environment using an uwb radio link, Selected Areas in Communications, IEEE Journal 20 (9) (2002) 1677–1683.
[38] Y.-C. Cheng, Y. Chawathe, A. LaMarca, J. Krumm, Accuracy characterization for metropolitan-scale wi-fi localization, MobiSys'05: Proceedings of the 3rd International Conference on Mobile systems, Applications, and Services, ACM Press, New York, NY, USA, 2005, pp. 233–245.
[39] A. Thangavelu, K. Bhuvaneswari, K. Kumar, K. SenthilKumar, S. Sivanandam, Location identification and vehicle tracking using vanet (vetrac), in: International Conference on Signal Processing, Communications and Networking, 2007. ICSCN'07, 2007, pp. 112–116.
[40] A. Boukerche, R.W.N. Pazzi, R.B. Araujo, A fast and reliable protocol for wireless sensor networks in critical conditions monitoring applications, MSWiM'04: Proceedings of the 7th ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems, ACM Press, New York, NY, USA, 2004, pp. 157–164.
[41] A. Boukerche, F.H.S. Silva, R.B. Araujo, R.W.N. Pazzi, A low latency and energy aware event ordering algorithm for wireless actor and sensor networks, MSWiM'05: Proceedings of the 8th ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems, ACM Press, New York, NY, USA, 2005, pp. 111–117.
[42] S. Capkun, M. Hamdi, J.-P. Hubaux, Gps-free positioning in mobile ad hoc networks, Cluster Computing 5 (2) (2002) 157–167.
[43] A. Savvides, C.-C. Han, M.B. Strivastava, Dynamic fine-grained localization in ad hoc networks of sensors, in: 7th ACM/IEEE International Conference on Mobile Computing and Networking, Rome, Italy, 2001, pp. 166–179.
[44] R.R. Brooks, S.S. Iyengar, Multi-Sensor Fusion: Fundamentals and Applications with Software, Prentice-Hall, Inc., Upper Saddle River, NJ, USA, 1998.
[45] T. Bass, Intrusion detection systems and multisensor data fusion, Communications of the ACM 43 (4) (2000) 99–105.
[46] C. Siaterlis, B. Maglaris, Towards multisensor data dusion for DoS detection, in: Proceedings of the 2004 ACM Symposium on Applied Computing (SAC), Nicosia, Cyprus, 2004, pp. 439–446.
[47] C. Intanagonwiwat, R. Govindan, D. Estrin, Directed diffusion: A scalable and robust communication paradigm for sensor networks, in: MobiCom'00: 6th ACM International Conference

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on Mobile Computing and Networking, ACM Press, Boston, MA, USA, pp. 56–67.

[48] R. Schubert, M. Schlingelhof, H. Cramer, G. Wanielik, Accurate positioning for vehicular safety applications – the safespot approach, in: Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th, Dublin, Ireland, 2007, pp. 2506–2510.

[49] J. Fernandez-Madrigal, E. Cruz-Martin, J. Gonzßlez, C. Galindo, J. Blanco, Application of uwb and gps technologies for vehicle localization in combined indoor-outdoor environments, in: ISSPA'07: International Symposium on Signal Processing and its Applications, Sharja (U.A.E.), 2007.

[50] J.C.F. Michel, M. Christmann, M. Fiegert, P. Gulden, M. Vossiek, Multisensor based indoor vehicle localization system for production and logistic, in: IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems, 2006, Heidelberg, 2006, pp. 553–558.

[51] S. Ammoun, F. Nashashibi, C. Laurgeau, Crossroads risk assessment using gps and inter-vehicle communications, IET Intelligent Transport Systems 1 (2) (2007) 95–101.

[52] M.E.E. Najjar, P. Bonnifait, A road-matching method for precise vehicle localization using belief theory and kalman filtering, Autonomic Robots 19 (2) (2005) 173–191.