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COVERAGE ESTIMATION IN SINERGIC NETWORKED INTELLIGENT TRANSPORTATION SYSTEMS WITH NON-ISOTROPIC NODES

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Safety of road travel is of the most considerable tasks solvable by intelligent transportation systems (ITS). It can be solved by mutual interaction of nodes equipped by sensors forming a sensor network. The wireless sensor networks can be integrated into ITS as vehicles through vehicle-to-vehicle or infrastructure-to-vehicle communication models to monitor the road condition, construction sites or obstacles for driving safety and to announce such road. Wireless sensor networks also pose a number of challenging optimisation problems. Coverage problem was and remains a fundamental issue in construction of wireless networks.

Most of known investigations, concerned with optimal (in sense of ensuring of necessary coverage level at every point in service area) deployment of networks' nodes, i.e., with optimal network topology, study the problem on the assumption that wireless network service area is free from obstacles, impeding normal propagation of information signals [1-3]. As a result, suggested network topologies become far from optimal at presence of obstacles within serviced area. More realistic solution presumes taking into account of obstacles within the serviced area.

Possible approaches for efficient placement of wireless network nodes on condition that service area contains obstacles are discussed at present work. Problem is examined from two points of view: as a probabilistic task, as well as a task of computational geometry. A probabilistic model is more realistic because the sensor design and environmental conditions are all stochastic in nature. Interference and noise in the environment can be modelled by stochastic processes. The investigation has resulted in some algorithms and considerations for near to optimal deployment of nodes within network service zone with obstacles.

Keywords: Intelligent Transportation System, anisotropic sensor, sensor network, coverage, service area

1. Introduction

Among the wide range of transportation problems, more or less successfully solvable by means of intellectual transportation systems (ITS), the road safety problem undoubtedly is the most significant. Such kind ITS, due to the real time processing of information, incoming both from onboard and road infrastructure sensors, give a chance to ensure on-time response on vehicle movement within the traffic stream.

Each sensor in its sensing range, gives a certain information type, whether on approaching obstacles or dynamically changing transport stream characteristics, such as velocity, acceleration, turns, oncoming vehicles, etc. Creation of ITS presupposes organization of transport flow participant interaction. Consequently, such ITS, are organized as ad hoc sensor networks, based both on infrastructure sensors and on-board ones.

One of the important tasks in ad hoc sensor network development is insurance of coverage over transport flow area should be controlled. In the most studied area of coverage problems (e.g. [1–5]), the sensing ability of sensors is abstracted as isotropic (a circular region or disk), and an event or target is detected in a binary sense, depending on whether it is inside such sensing disk or not. To the contrary, in real life situations most of sensors, being used in the ITS, such as cameras, directional microphones, radars, etc. have anisotropic coverage area, represented by directional sector and determined both by its location and orientation.

Coverage estimation and optimal placement of anisotropic sensors, forming sensor network, still remains insufficiently studied. In this paper several approaches that can be applied to such type of tasks are overviewed and evaluated. A few typical traffic scenarios are discussed as well as corresponding approaches for anisotropic coverage evaluation and optimal sensor placement.

2. Sensory Devices

The intersection collision avoidance (ICA) is one of the significant issues in developments of intelligent traffic system. At many intersections, some buildings or trees may obscure the crossing traffic near the road or other vehicles. Moreover, the vehicle sensors cannot often detect the threat conditions alone. Development of intersection collision countermeasures systems is a crucial and urgent challenge.

For preventing of potentially dangerous transport situations it is essential to know relative position and velocity, direction and acceleration of transport traffic participants .Such kind information can be obtained either explicitly or implicitly, depending on type of information sensors employed.

In ICA systems, the positioning of the vehicles in lanes should be very accurate within some required tolerances before the vehicles cross the intersection. For instance, a vehicle will move 20m in 1 second if its speed is 72 km/hr. ICA system architecture has to provide a mechanism to acquire reliable positioning of the approaching vehicles at an intersection. In general, the positioning accuracy tolerance is less than 1 m for a moving vehicle approaching the intersection with 100 km/hr.

Taking into consideration specifics of given task, following sensor types could be applicable for ITS: microwave radars, ultrasonic and infrared range sensors. Sensing range of these sensors can reach up to 250 meters distance. Sensing zone, as a rule, represents a sector of a disk. For instance, FMCW radar systems have an aperture angle within 60^o in horizontal plain and 5^o in vertical plane.

In Figure 1, the subscript *i* denotes the specified properties in Lane *i* of an intersection, e.g., D_i is the horizontal distance of a vehicle from the radar sensor at the intersection, $D_{max,i}$ and $D_{min,i}$ denote the maximal and minimal distances measured by the radar sensor, respectively, $D_{F,i}$, and $D_{R,i}$, respectively denote the front and rear buffer distances of the measured vehicle, H_i is the height of the sensor, R_i is the range between the sensor and the vehicle, V_i is the speed of the vehicle, $\Delta\theta_i$ is the bore size angle of the radar transmitter, and the inclination angle of radar antenna is equal to $\theta_i + \frac{\Delta\theta_i}{2}$. H_i, θ_i, and $\Delta\theta_i$ are assigned when the radar system is installed. $D_{F,i}$ and $D_{R,i}$, depend on the traffic conditions of different lanes and can be assigned. $D_{F,i}$ and $D_{R,i}$, are suggested to be longer if the speed limit of the lane is higher. They can overcome the positioning errors and can comply with the safety requirements. In addition, R_i and V_i can be measured by this radar system [9].

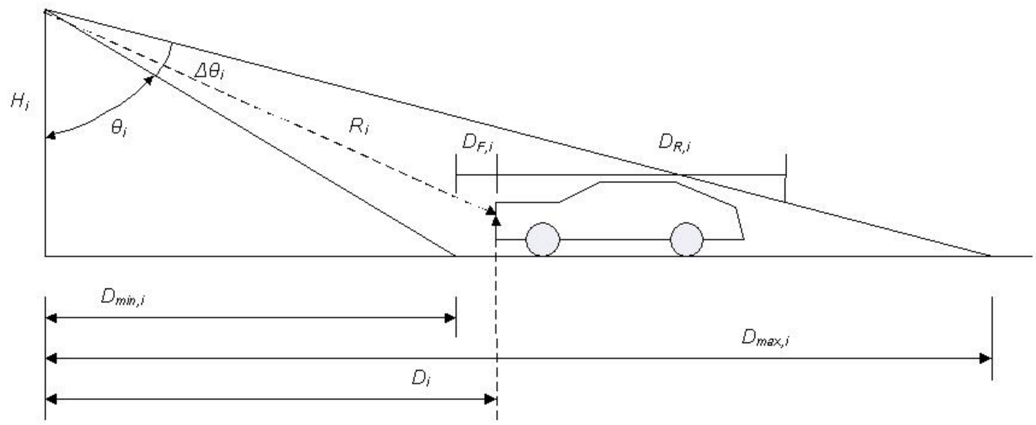

Figure 1. The configuration of the radar system in Lane *i* of an intersection

Figure 1 shows a typical configuration of the radar system in Lane i at intersections for the ICA system. An overhead mounted microwave radar system transmits energy to an object and receives the reflected energy from a measured object. The reflected signal from a vehicle can be used to detect the positions, speeds, presences, lane occupancy, and passages of vehicles in the lane. There are two types of microwave radar sensors used in roadside applications. One is the continuous wave Doppler radar utilized to measure the speed of vehicles. The other is the frequency modulated continuous wave (FMCW) radar utilized to detect the positions of vehicles usually. The measured range, R_i, can be

$$R_i = \frac{c\Delta f_i}{4 f_{m,i}\Delta F_i}, \tag{1}$$

where c is the light speed, Δf_i is the instantaneous difference in frequency of the transmitter at the times the signal transmitted and received, $f_{m,i}$, is radio frequency (RF) modulation frequency, and ΔF_i is the bandwidth of the modulated frequency. The range resolution, ΔR_i , resolved by an FMCW radar is

$$\Delta R_i = \frac{c}{2\Delta F_i}. \tag{2}$$

In case the radar operates in 10.5GHz band with the bandwidth 45MHz, the range resolution is 3.3m at best.

Comprehensive facilities open up since vehicles more and more widely are being provided with the global positioning system receivers, giving the coordinates of the vehicle, equipped with such a receiver. In any case, Prevention of accidents is reached by sharing of the information from the both vehicle onboard and transportation infrastructure sensors. It is obvious that all objects involved should be equipped with communications facilities.

Two types of communications are possible, namely, Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. In the V2V, vehicles are equipped with sensors in order to exchange information that is crucial to avoid severe situations like traffic jam avoidance. In V2I, information flow from vehicles to sensors installed on roadway infrastructure. This communication is necessary in propagating awareness about traffic conditions, especially on highways, to support safer commuting.

3. Traffic Scenarios

There are several typical traffic scenarios [6], which may lead to potential accidents and then it is shown how the potential accidents can be avoided, if the vehicles involved in these situations are equipped with sensors and have communicating capabilities to exchange data with other vehicles in the inter-vehicle network.

Rural area with single lane traffic

Considering the typical traffic situation depicted on Figure 2, three vehicles A, B and C are shown on the road. Initially, assume that the vehicles are not equipped with any sensors and are not part of any sensor network. Vehicle A and vehicle C cannot see each other. If vehicle A tries to overtake vehicles B, it may collide with the approaching vehicle C. These types of accidents can be avoided with the help of sensors and intelligent sensor networks. Now, consider that vehicles A, B and C are equipped with front-collision avoidance sensors using millimetre-wave radar or scanning laser. They also must have communication capability, so that they can exchange sensors' data among themselves. Vehicles B and C can sense each other and so can vehicles A and B. So vehicle A knows that there is a vehicle approaching i.e. vehicle C and it will not overtake.

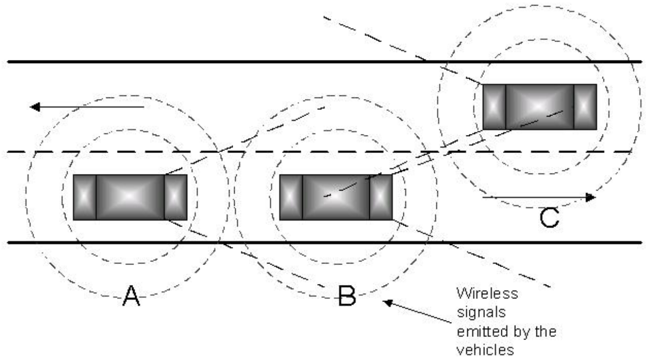

Figure 2. Traffic on a bridge or in a rural area

Freeway: Entry and Exit ramps

Ramps, being the entries and exits of freeway systems, usually are places where many high velocity accidents take place because of the merging traffic and variation of the vehicle speed. Consider the case shown on Figure 3. It shows an entry ramp onto a freeway. Vehicle A and vehicle C cannot see each other and this may lead to a collision since vehicle A wants to enter the lane. But if the vehicles can exchange data among them, then this can be avoided. As soon as vehicle A nears the ramp it becomes a part of the ad hoc network and joins vehicle B and C. So now vehicle C knows that there is a vehicle entering from the ramp and it can adjust its speed to let vehicle A merge in between itself and vehicle B.

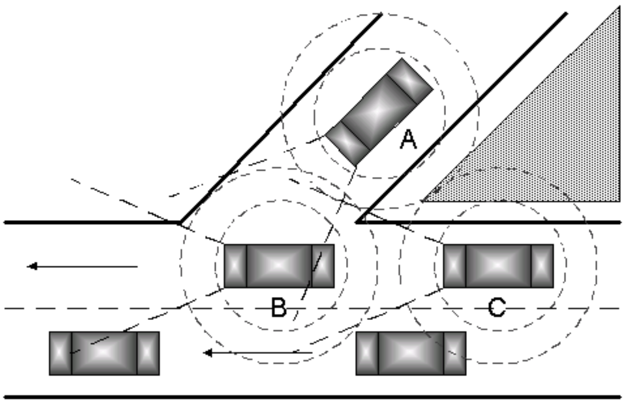

Figure 3. Typical situation at an entry ramp

Street Corners

The traffic patterns at street corners are unpredictable and can often lead to dangerous situations. On Figure 4, vehicle A wants to overtake vehicle B. Vehicle A cannot see vehicle C. If vehicle A changes the lane to overtake vehicle B it may collide with the approaching vehicle C. This could be avoided if the vehicles can exchange data. If vehicle B is equipped with vision sensors, it can sense vehicle C and send a signal to vehicle A that vehicle C is approaching. So vehicle A will not overtake and the collision will be avoided. The data flow from vehicle C to vehicle A has to pass through vehicle B.

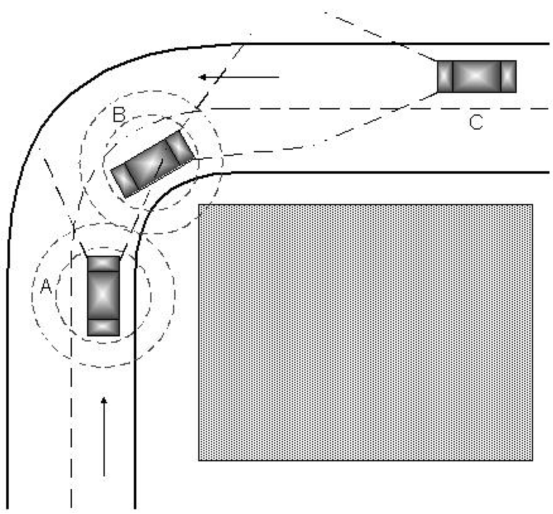

Figure 4. Corners like these host many accidents due to driver misjudgement around the blind turn

Intersections

Even though the common ITS infrastructure based safety system may exist at certain intersections, still, a networked approach for communication among vehicles can increase the level of safety. On Figure 5, a traffic scenario at a road intersection is shown. Assume that the signal for the horizontal lanes has been turned green and consequently the signal for the vertical lanes is red. Vehicle B wants to make a right turn while vehicle A wants to proceed straight from left to right. Neither of the vehicles can see each other due to vehicle C. If the vehicles are able to communicate with each other, then vehicles A, B, D, E and F could form a sensor network and could communicate with each other. A and B can use their sensed data and data from other vehicles to avoid a collision even though vehicle C is blocking the direct line-of-sight view between them. Each vehicle would know the position and the velocity of the other vehicle using area coverage techniques and would take appropriate measures to avoid the accident and cross the intersection safely. The major challenges in such cases are that, there being many vehicles in its communication range, vehicle B should be able to obtain only those data which are useful while neglecting data from other vehicles. On Figure 4, vehicle G has already turned right, so its information is not useful for vehicle B and hence should be neglected.

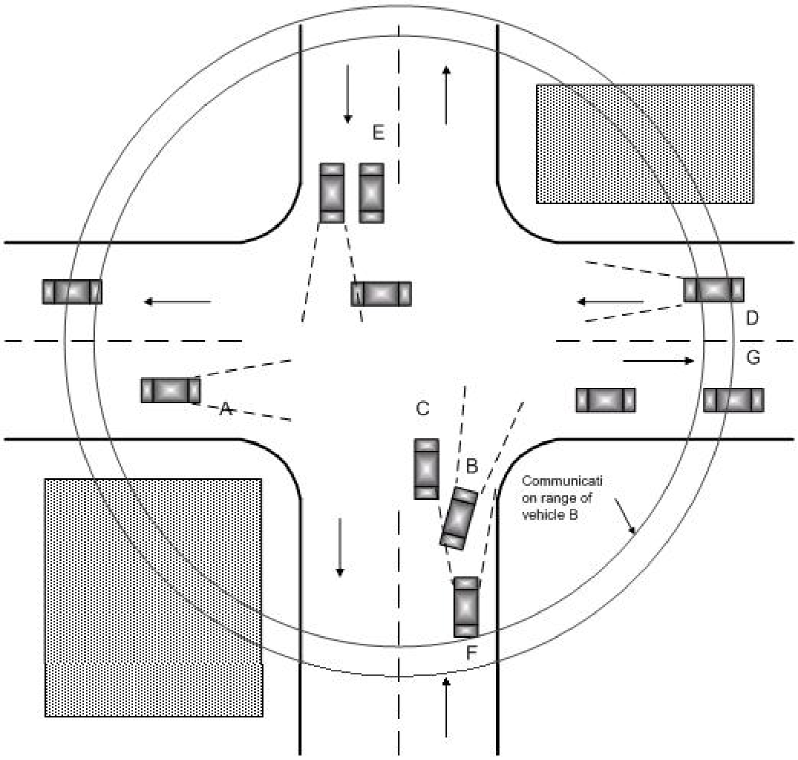

Figure 5. Vehicles at an intersection

4. Coverage in Sensor Networks

The millimetre-wave radar can be used for detecting the distance of obstacles or other vehicles. It can detect targets even during stormy conditions and simultaneously measure both the target's distance and its relative velocity. Common, isotropic sensors detection model can be described as (3),

$$p(d) = \frac{K}{d^k}, \tag{3}$$

where K – is the energy emitted, κ – is the decay coefficient and d – is the distance between the sensor and the object. The sensing power of such sensors can be expressed as a normally distributed function as shown in equation 4. The sensing model follows a Gaussian distribution with mean μ and variance σ.

$$p(d \mid \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(d-\mu)^2}{2\sigma^2}}. \tag{4}$$

When the sensing ranges of vehicles overlap, the sensing strength in the overall area around the vehicles also increases. This in turn increases the probability of detection of any other sensors or obstacles or other vehicles without sensors which may enter that area. Hence, this leads to the overall increase of sensing ability of the sensors in that area (5).

$$p = 1-(1-p_1)(1-p_2)(1-p_3)\,, \tag{5}$$

where p is the total probability of detection and p_1, p_2 and p_3 are the probabilities of detection of individual sensors.

In the above detection fusion scheme, the distance between two sensors/vehicles is very important. In case when V2I communication scheme is possible, additional road infrastructure based sensors can be used to increase resulting detection probability.

However, most of the sensors such as cameras, directional microphones, radars etc are anisotropic. And its coverage area can be described rather as a sector than a circular region (Fig. 6). This makes network coverage evaluation task much more complicate. Several possible approaches to coverage evaluation for an anisotropic sensor net coverage overviewed in the next section.

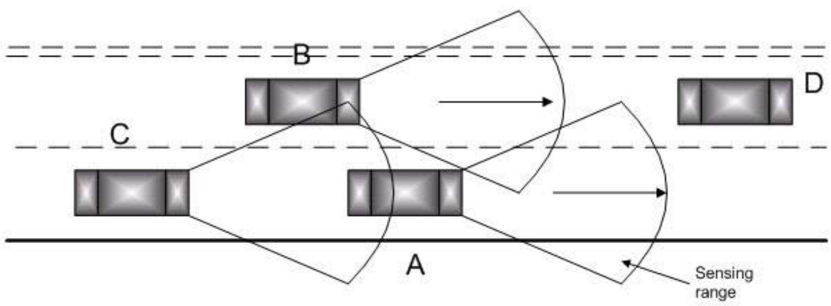

Figure 6. Vehicles with MMW radar on the road

5. Approaches to Coverage Evaluation

Geometric Approach

The following parameters completely characterize the sensing sector of an anisotropic sensor node $i.\left(x_i, y_i\right)$: the Cartesian coordinates that denote the location of the sensor in a two-dimensional plane. θ: the field of view (FOV), describing the maximum angle of sensing achieved by directional sensor. R_s: maximum sensing range of the sensor, beyond which a target will not be detected in a binary detection sense. $\overrightarrow{d_{i,j}}$: a unit vector which cuts the sensing sector into half. This parameter defines the orientation of the directional sensor.

It is assumed that a directional sensor can only take a finite set of orientation set of orientations. For example, a directional sensor with $\frac{\pi}{4}$ of FOV can pick eight orientations with mutually disjoint sensing sectors which can be combined to generate the full circular view of an isotropic sensor. With each choice of orientation, a certain subset of targets is covered by the directional sensor.

The relationship of a directional sensor, its orientation and a target can be determined by a Target in Sector (TIS) test [7]. The TIS test can be described as follows. Consider a target k located at $\overrightarrow{t_k}$ and a directional sensor i located at $\vec{l_i}$. In order to determine whether the target k can be sensed by the directional sensor i with the j-th orientation, we follow the following steps:

Calculate the distance vector $\overrightarrow{v_{i,k}}$, pointing from the directional sensor i to the target k $\overrightarrow{v_{i,k}} = \overrightarrow{t_k} - \vec{l_i}$. Check whether the resulting distance vector is within the FOV of the directional sensor i by performing the inner product operation:

$$\vec{d}_{i,j}^{T} \cdot \vec{v}_{ik} \geq \left\| \vec{v}_{ik} \right\|_2 \cos\left(\frac{\theta}{2}\right). \tag{6}$$

Then verify whether or not target k is within the sensing range of the directional sensor i or not by checking

$$\left\| \vec{v}_{ik} \right\|_2 \leq R_s , \tag{7}$$

with equality when the target k is on the arc of the sensing sector of the directional sensor i.

If both (6) and (7) hold, the result of the TIS test is true (i.e. node i covers the target k if it sets its orientation to j) otherwise, it is false.

Let Φ_{ij} denote the set of targets that are covered by sensor i when its orientation is j. Then we can determine all the sets $\Phi_{ij} \forall i, j,$ by running the TIS test for every i ,j.

Voronoi Tessellation Based Approach

The approach is based on Voronoi tessellation. The consideration of a general anisotropic sensor model results in an anisotropic Voronoi tessellation which is difficult to analyse. Therefore the optimal control law for the coverage problem is derived assuming a fixed, equal sensor orientation and a specific class of anisotropic sensors with elliptic sensing performance level sets is assumed instead of circles as for the isotropic case. The idea is to transform the anisotropic problem to the isotropic one. By the transformation properties the control law obtained for the isotropic problem also solves the problem for the considered anisotropic case (Fig. 7).

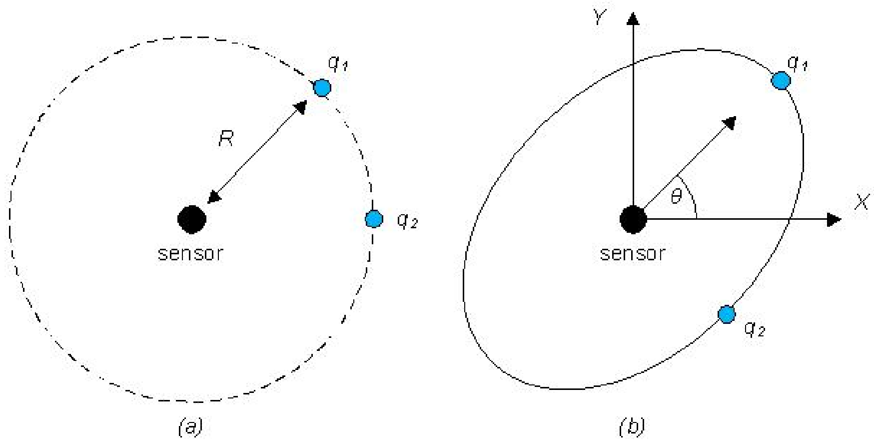

Figure 7. (a) Isotropic sensor model, (b) Anisotropic sensor model

Euclidean distance measure the Voronoi region [8] V_i associated with its generator p_i is defined as:

$$V_i^* = \left\{ q \in Q \mid \left\| q - p_i \right\|_{L_i} \leq \left\| q - p_j \right\|_{L_i}, \forall j \neq i \right\}. \tag{8}$$

Where the sensing performance defined as $f\left(\left\| q - p_i \right\|\right)$ that degrades with the distance between a point $q \in Q$ and the i-th sensor position p_i. The points where probability is equal are represented by a circle of radius R, and the centre is the sensor location. Point's q_1 and q_2 with the same distance to the sensor will result to the same sensing probability. The sensing performance of the anisotropic sensor model is given by the non-Euclidean distance measure defined as $\left\| q - p_i \right\|_{L_i}^2 = \left(q - p_i \right)^T L_i \left(q - p_i \right)$, where the matrix L_i is positive definite and can be decomposed as $L_i = F_i^T F_i$, with

$$F_i = \left[\begin{pmatrix} \dfrac{c}{a} & 0 \\ 0 & \dfrac{c}{b} \end{pmatrix} \begin{pmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{pmatrix} \right], \tag{9}$$

where θ_i is the orientation of the i-th sensor, and $a,b,c > 0$ are the parameters.

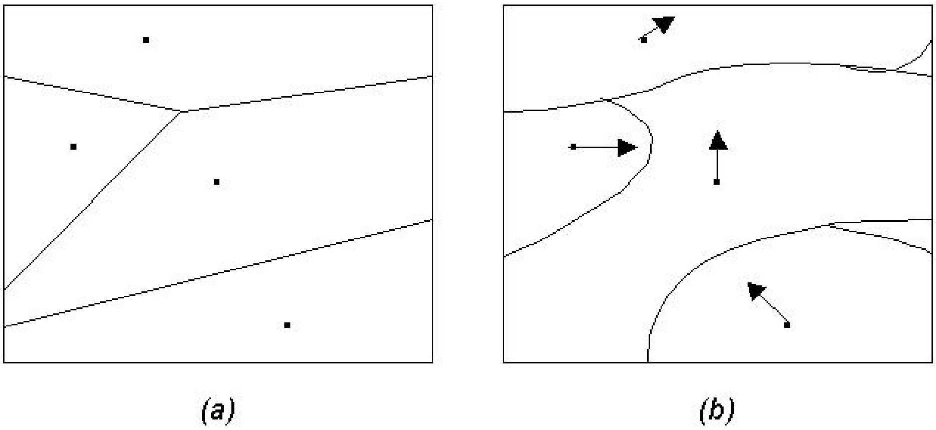

Figure 8. (a) Isotropic Voronoi partition, (b) anisotropic Voronoi partition

This anisotropic Voronoi partition is not only determined by the sensors position but also the sensor orientation θ_i as observable from matrix L_i. As a result the anisotropic Voronoi tessellation is no longer composed of convex polytopes, but of curved possibly non-convex regions (Fig. 8). Major difference to isotropic Voronoi tessellations is that anisotropic tessellations may contain regions without a generator, i.e. Voronoi cell of an anisotropic Voronoi diagram is not necessarily connected.

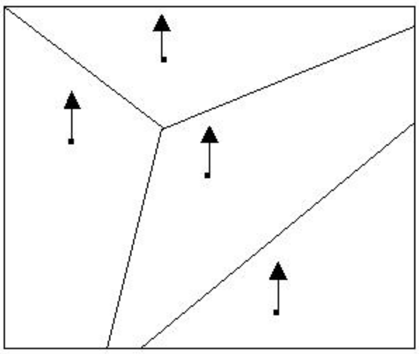

Figure 9. Anisotropic Voronoi partition with equal orientation

To avoid this problem, another assumption should be considered. The orientations of all agents are equal and fixed over time, i.e. $\theta_i(t) = \theta_j(t), \forall_i \neq j$ and $t \geq 0$. One example of the anisotropic Voronoi diagram with fixed and equal orientation is shown in Fig. 9. Worth to mention, that such assumption significantly reduces described method relevance.

Probabilistic Approach

A more realistic model of anisotropic sensor is considered. Instead of using the Voronoi approach where each sensor is assumed to have its own sensing region and the joint detection probability approach applied [8].

This model depends on the distance and orientation from the sensor to the target in the region of interest. Let $S = (s_1, ..., s_n)$ be the location of the *n* identical sensors located in the region *Q*. Each sensor has a limited sensory domain Q_i with the maximum sensing range R and the maximum sensing direction Θ (Fig. 10). The sensing ability of each sensor declines along the radial distance and the radial angle from the sensor to the point to be sensed.

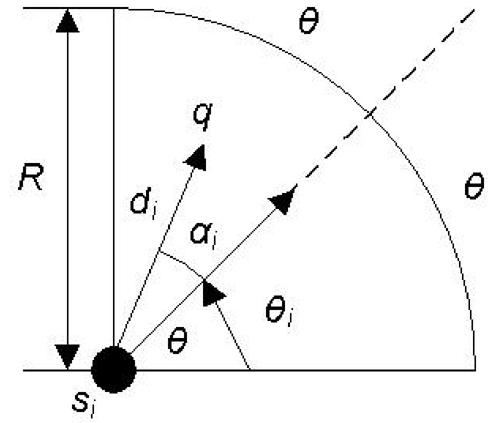

Figure 10. Limited-range anisotropic sensor model

The sensing performance of sensor *i* depends on the distance d_i and the orientation a_i from sensor *i* to the target *q*. Mathematically, the sensory domain of each sensor is given by

$$Q_i = \{q \in Q : d_i \le R \wedge |\alpha_i| \le \Theta\}, \tag{10}$$

where:

$$\begin{aligned} &d_i = \|q - s_i\|, \\ &\alpha_i = \cos^{-1}\left(\frac{(q - s_i)(\cos\theta_i, \sin\theta i)}{\|q - s_i\|}\right), \\ &\Theta \in \left(0, \frac{\pi}{2}\right]. \end{aligned} \tag{11}$$

Moreover the following assumption on the sensing performance of the above sensor model is made.

$$p_i(q) = 0, \frac{\partial p_i(q)}{\partial d_i(q)} = 0, \ \frac{\partial p_i(q)}{\partial \alpha_i(q)} = 0 \text{ if } q \notin Q_i . \tag{12}$$

The assumption tells that the sensor *i* can only sense the point inside its region of sensing Q_i. Hence example of the sensor model will be:

$$p_i(q) = \begin{cases} \dfrac{(d_i - R)^2 (\alpha_i - \Theta)^2}{R^2 \Theta^2} & \text{if } q \in Q_i \\ 0 & \text{otherwise} \end{cases} . \tag{13}$$

This approach is effective to tackle some problems faced in the Voronoi based approach for the anisotropic sensor model i.e. the anisotropic Voronoi tessellations, which is difficult to analyse.

6. Conclusions

Present study presents a promising outlook on application of sensor networks in intellectual transportation systems. The parameter analyses of the ICA system based on radar sensor, basic scenarios of the situations, which safety can be essentially improved by using sensor controls located on vehicles, and integrated with a road infrastructure are considered.

The problems arising at designing of similar networks, in particular, a problem of an estimation of a coverage zone, are analysed. The most known methods of an estimation of network coverage are overviewed and advantages and lacks of the specified methods are conceptually considered.

As it is possible to see from the review, the geometrical method of estimation has the serious lacks limiting its application. First of all, to estimate coverage of object that is subject to detection its coordinates should be known in advance. Also it is impossible to calculate probability of object detection as the method states only a binary estimation – in a zone/not in a zone.

The method based on the Voronoi diagram though is one of the most effective, for networks with isotropic sensor controls, assumes not quite realistic assumptions for anisotropic sensor controls. The elliptic form of a covering isn't characteristic for the sensor controls applied in areas considered in work as well as probability of identical orientations of all sensor controls is insignificant. In a case of assumption of identical orientation of sensor controls discarding, such diagram can't be used, in case of need, for sensor controls placement optimisation by Lloyd's algorithm since it will have regions without corresponding generators. This circumstance reduces its value.

Probabilistic approach appears to be the most perspective from presented approaches since it gives the chance to consider not only probability of a covering for each separate sensor control, but also total probability in case of overlapping of zones. The method can be scaled for *n* measured space, and in need of optimisation of sensor controls placement can be used in McQueen's algorithm since this algorithm doesn't demand construction of the Voronoi diagram, and calculated probability of detection of object can be used as the metrics.

Suitability, algorithms and efficiency of the given method for a sensor networks covering estimation in considered ITS typical scenarios further can become a subject of the subsequent researches.

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