Cooperative Localization for the Internet of Things

Marco A. M. Marinho*, Alexey Vinel*, Edison P. de Freitas†, and Stephanie M. A. Fernandez‡
*Halmstad University, School of Information Technology, Halmstad, Sweden
†Federal University of Rio Grande do Sul (UFRGS), Informatics Institute, Porto Alegre, Brazil
‡University of Brasília (UnB), Department of Electrical Engineering (ENE), Brasília, Brazil

***Abstract*—The internet of things (IoT) currently has a large range of applications, from wearable to smart cities. Many of these applications require that the nodes inside the networks know their relative or absolute position. To this end, multiple positioning methods can be applied, among such methods are Global Positioning Systems (GPS) or methods that employ time delay of arrival (TDOA). This work presents node localization methods that employ a dual polarization receiver on a single node, or a virtual array when multiple nodes are capable of cooperating. The proposed approaches aim to minimize the economic cost associated with implementing localization methods, and can be done with simple hardware. The accuracy of the proposed methods is measured trough a set of numerical simulations.**

***Index Terms*—Radio Localization, Cooperative Localization, Internet of Things**

I. Introduction

The internet of things (IoT) have seen applications on very broad and diverse fields. Applications range from topics such as smart cities and commercial usage to environmental monitoring and health care [1]. Within the large scope of such applications, many specific applications require knowledge about the position, relative or absolute, of the devices that make up the network.

Absolute positioning can be estimated by making use of well know methods such as Global Navigation Satellite Systems (GNSS). However, many nodes that compose typical IoT networks are expected to have simple hardware. Furthermore, in many cases, these nodes also posses very limited energy reserves. Therefore, GNSS can become an impractical or even impossible solution.

Many different alternatives for relative node localization have been proposed. One such approach is based on estimating the distance between nodes by employing the received signal strength indicator (RSSI) [2], however, such approach often leads to inaccurate values that can cause errors in the positioning system due to its susceptibility to noise in the environment.

Another proposed method is by measuring hop sizes between nodes and their neighbors. The DV-hop method [3] provides an estimate of the relative position of nodes inside a network without requiring additional hardware and while offering better precision than RSSI based methods. Still, the method performance is impacted by the nodes placement, thus improvements in the positioning accuracy and location coverage are obtained when uniform nodes placement instead of random nodes placement.

Other methods rely on analyzing behavior of users and the correlation between the behavior of different users to trace their position inside a network. In [4] a location prediction scheme that leverages cellular calls to enhance location prediction accuracy is presented. Nevertheless, the proposed method requires some specific trajectory data in order to be applied.

The time of arrival (TOA) is also employed to estimate the distance between pairs of nodes. In [5] a method employing TOA based on measuring the propagation delay of sound waves is presented. The proposed method can be applied with cheap hardware and can achieve a positioning precision close the half a meter. However, the proposed method can be considered feeble in noisy environments.

Another important alternative is the use of direction of arrival (DOA) based methods [6]. DOA can be employed by measuring the relative angle of arrival of a signal at a given node that acts as the reference position. With multiple DOA estimates obtained, an estimate of the position of the transmitting node can be calculated. Many different algorithms for DOA estimation can be used, however, most algorithms rely on the presence of antenna arrays.

In this paper we present a cooperative approach for node localization using DOA estimation. The approach employs virtual array when the network node density is sufficiently large, as well as utilizing dual polarized antenna elements, such as a crossed dipole antenna, to obtain estimates of the relative positions of nodes inside a network.

The remainder of this paper is divided into six sections. In Section II the problem tackled in this work is presented. In Section III the mathematical model assumed for the physical layer is presented. Section IV presents the proposed single node localization approach, while Section V presents the proposed cooperative virtual array method. In Section VI the results of a set of numerical simulations are presented and analyzed. Finally, conclusions are drawn in section VII.

II. Problem Description

This work assumes a network consisting of K nodes placed at coordinates $S_1, S_2, ..., S_K$ where

$$S_1 = [x_1, y_1]. \tag{1}$$

Furthermore, the presence of a set of nodes $S_i, ..., S_j$, whose position information is known a priori, is also assumed. The proposed method requires

$$|i, ..., j| \geq 3. \tag{2}$$

Finally, for the proposed single node localization method, it is assumed that the orientation of all nodes is known with respect to a common reference.

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III. Signal Model

A propagating electromagnetic wave can have its electric field written as

$$\boldsymbol{E} = -E_x \boldsymbol{e}_x + E_y \boldsymbol{e}_y, \tag{3}$$

here, E_x and E_y are the horizontal and vertical vectors of the electric field. A polarization ellipse can be defined with such vectors, as shown in Figure 1.

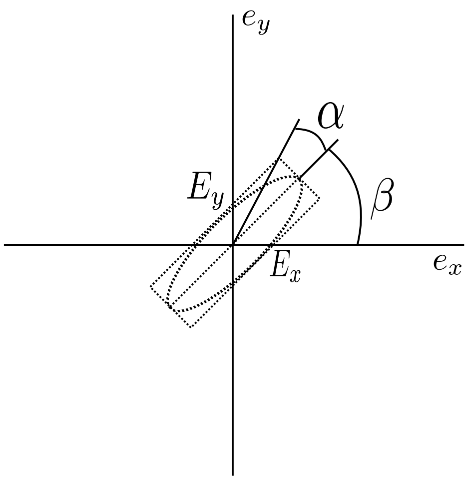

Fig. 1. Polarization ellipse

The electric field components can be rewritten with respect to the electric angles α and β as

$$\begin{aligned} E_x &= \boldsymbol{E}\cos(\gamma) && (4)\\ E_y &= \boldsymbol{E}\sin(\gamma)\mathrm{e}^{j\eta}, && (5)\end{aligned}$$

where

$$\begin{aligned} \cos(2\gamma) &= \cos(2\alpha)\cos(2\beta) && (6)\\ \tan(\eta) &= \tan(2\alpha)\csc(2\beta), && (7)\end{aligned}$$

2γ, 2β, and 2α form the sides of a spherical right triangle, as shown in Figure 2.

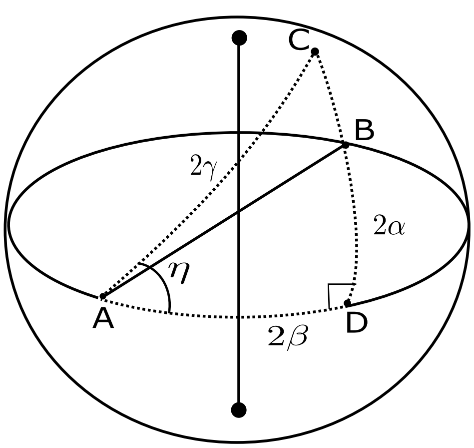

Fig. 2. Poincaré sphere

The received wavefront at a crossed dipole with its antenna elements parallel to the $x-$ and $y-$axis of the polarization ellipse generates an output proportional to the incoming vectors E_x and E_y respectively, and can be written as

$$\begin{aligned} \boldsymbol{E} &= (-E_x)\boldsymbol{e}_x + (E_y\cos(\theta))\boldsymbol{e}_y && (8)\\ &= \boldsymbol{E}\left(-\cos(\gamma)\boldsymbol{e}_x + \sin(\gamma)\cos(\theta)\mathrm{e}^{j\eta}\boldsymbol{e}_y\right), && (9)\end{aligned}$$

here θ is the angle of arrival of the received wavefront with respect to the $x-$axis.

The received signal can then be written in matrix form as

$$\boldsymbol{X} = \boldsymbol{u}\boldsymbol{s} + \boldsymbol{N}, \tag{10}$$

where $\boldsymbol{X} \in \mathbb{C}^{2\times N}$ is a matrix with measured outputs at each of the dipole elements, N is the number of snapshots, $\boldsymbol{s} \in \mathbb{C}^{1\times N}$ is the vector containing the transmitted signal, $\boldsymbol{N} \in \mathbb{C}^{2\times N}$ contains Additive White Gaussian noise, and the polarization vector $\boldsymbol{u} \in \mathbb{C}^{2\times 1}$ is given by

$$\boldsymbol{u} = \begin{bmatrix} -\cos(\gamma) \\ \sin(\gamma)\cos(\theta)\mathrm{e}^{j\eta} \end{bmatrix} \tag{11}$$

according to (9). For the remainder of this work it is assumed that all polarization components are known at all nodes of the network.

Assuming the network is dense enough, the nodes may be spaced sufficiently close to be treated as an antenna array. In this case, the received signal across the M nodes that constitute this array can be written as

$$\bar{\boldsymbol{X}} = (\boldsymbol{a} \diamond \boldsymbol{u})\,\boldsymbol{s} + \bar{\boldsymbol{N}}, \tag{12}$$

where $\bar{\boldsymbol{X}} \in \mathbb{C}^{2M\times N}$, $\diamond$ stands for the Khatri-Rao product, or the column wise Kronecker product, $\bar{\boldsymbol{N}} \in \mathbb{C}^{2M\times N}$, and

$$\boldsymbol{a} = [1, e^{j\mu}, \cdots, e^{(M-1)j\mu}]^{\mathrm{T}}, \tag{13}$$

where

$$\mu = 2\pi\frac{\Delta}{\lambda}\sin\theta, \tag{14}$$

here, Δ is the separation between antenna elements, and λ is the wavelength of the incoming signal.

IV. Single node localization approach

The proposed approach consists of estimating the angle of arrival of a received signal by looking at the ratio between the different polarization outputs of the crossed dipole. The ESPRIT [7] algorithm can be used to estimate this ratio by constructing the covariance matrix $\boldsymbol{R}_{\boldsymbol{XX}} \in \mathbb{C}^{2\times 2}$ of the received signal

$$\boldsymbol{R}_{\boldsymbol{XX}} = \frac{\boldsymbol{X}\boldsymbol{X}^{\mathrm{H}}}{N}, \tag{15}$$

where $(\cdot)^{\mathrm{H}}$ represents conjugate transposition. Next, an eigen-decomposition of $\boldsymbol{R}_{\boldsymbol{XX}}$ is calculated

$$\boldsymbol{R}_{\boldsymbol{XX}} = \boldsymbol{\Gamma}\boldsymbol{\Lambda}\boldsymbol{\Gamma}^{-1}. \tag{16}$$

Since, at any given carrier frequency, only one node is transmitting during a given time slot, the signal subspace $\boldsymbol{E}_{\boldsymbol{s}} \in \mathbb{C}^{2\times 1}$ can be reconstructed by selecting the eigenvector

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related to the largest eigenvalue. An estimate of the ratios between the two polarizations can be obtained by

$$r = \left| \frac{\boldsymbol{E_s}[2]}{\boldsymbol{E_s}[1]} \right|. \tag{17}$$

Considering that the ratio is given by

$$\frac{-\cos(\gamma)}{\sin(\gamma)\cos(\theta)\mathrm{e}^{j\eta}}, \tag{18}$$

the angle θ can be obtained by

$$\theta = \cos^{-1}\left(\frac{-\cos(\gamma)}{r\sin(\gamma)\mathrm{e}^{j\eta}}\right). \tag{19}$$

The DOA is given with respect to the reference of the $\boldsymbol{x}-$axis. Thus, it is impossible to distinguish from which direction the signal is received. Figure 3 highlights this problem.

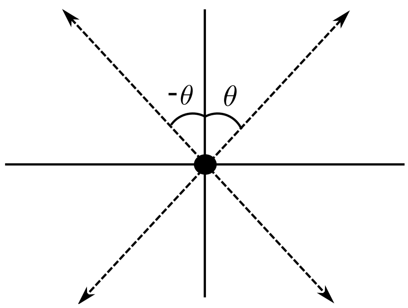

Fig. 3. Depiction of possible ambiguity in signal propagation direction

Furthermore, from Figure 3 it is clear that θ ranges from $[-\pi, \pi]$, making it impossible to pinpoint, without ambiguity, the sector from which the signal is received, as the only known parameter is $\cos(\theta)$. Therefore, each node has two line estimates in the ground plane that represent possible positions for the transmitting node. However, once a set of such lines is acquired, an estimate of the transmitting sensor position can be obtained. Figure 4 presents an example of estimates from three nodes which are employed to estimate the position of a single transmitting node. The problem can be written as the least squares problem of finding the point with minimum distance to the line estimates.

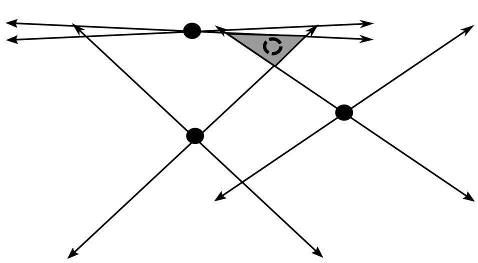

Fig. 4. Sensor triangulation example using only the DOAs of the reference nodes

By writing the line equations of the estimated lines, an estimate of the node location can be found by solving

$$\begin{aligned}\{\hat{x}_0, \hat{y}_0\} = \min_p & \frac{|A_{p_1}x_0 + B_{p_1}y_0 + C_{p_1}|}{\sqrt{A_{p_1} + B_{p_1}}} \\ & + \frac{|A_{p_2}x_0 + B_{p_2}y_0 + C_{p_2}|}{\sqrt{A_{p_2} + B_{p_2}}} + ..., \end{aligned} \tag{20}$$

where p is the index of a set containing the possible combinations of estimated lines. More than three node estimations can be used for increased accuracy at the cost of higher computational load. The final location estimate $S_0 = [x_0, y_0]$ is given by taking the first derivative of Eq. (20) with respect to x_0 and y_0 and finding the point where it equals to zero.

V. Virtual Array Localization Approach

Another possible approach for estimating node positions inside a network is by employing virtual antenna arrays if the network is dense enough. This might be achievable in cases where a person has multiple connected wearable devices on a body area network (BAN), for instance, on a health care setting. For this method, we assume that the node that will constitute the virtual array have an estimate of the position with respect to each other, this can be achieved by following the method proposed in Section IV. With these estimates in hand, the nodes can constitute a virtual array be employing array interpolation. Array interpolation technique consists of finding a transformation matrix $\boldsymbol{B}$ that maps the real response $\boldsymbol{a}$ into a desired response $\bar{\boldsymbol{a}}$. Thus, matrix $\boldsymbol{B}$ is the matrix that provides the best transformation between vectors $\boldsymbol{a}$ and $\bar{\boldsymbol{a}}$. This work employs a least squares fit [8] for obtaining $\boldsymbol{B}$, defined as

$$\boldsymbol{B} = \bar{\boldsymbol{a}}\boldsymbol{a}^{\dagger} \in \mathbb{C}^{M \times M}, \tag{21}$$

where $(\boldsymbol{.})^{\dagger}$ stands for the Moore–Penrose pseudo-inverse.

Once $\boldsymbol{B}$ is obtained, an estimate of the angle of arrival with respect to the virtual antenna array can be obtained using ESPRIT. The singular value decomposition (SVD) of $\bar{\boldsymbol{X}} \in \mathbb{C}^{2M \times N}$ is given by

$$\bar{\boldsymbol{X}} = \boldsymbol{U}\boldsymbol{\Lambda}\boldsymbol{V}^{\mathrm{H}}, \tag{22}$$

here, $\boldsymbol{U} \in \mathbb{C}^{2M \times 2M}$ and $\boldsymbol{V}^{N \times N}$ are the left-singular and right-singular vectors of $\bar{\boldsymbol{X}}$, $\boldsymbol{\Lambda} \in \mathbb{C}^{2M \times N}$ contains the singular values of $\bar{\boldsymbol{X}}$. The signal subspace $\boldsymbol{E}_S \in \mathbb{C}^{2M \times 1}$ of $\bar{\boldsymbol{X}}$ is constructed by selecting the singular vectors related to the largest singular value. The noise subspace is composed of the remaining singular vectors $\boldsymbol{E}_N \in \mathbb{C}^{2M \times 2M-1}$ of $\bar{\boldsymbol{X}}$.

An estimate for θ can be obtained by solving

$$\boldsymbol{J}_1\boldsymbol{E}_S\boldsymbol{\Phi} = \boldsymbol{J}_2\boldsymbol{E}_S, \tag{23}$$

where $\boldsymbol{J}_1$ and $\boldsymbol{J}_2$ select the first and last M2-1 rows of $\boldsymbol{E}_S$, $\boldsymbol{\Phi}$ is a matrix whose eigenvalues relate to θ by

$$\theta = \arcsin\left(-\frac{\arg(v)}{2\Pi\Delta}\right), \tag{24}$$

where v is the eigenvalue of $\boldsymbol{\Phi}$ and Δ is the separation between the elements of the virtual array.

Once a DOA estimate is obtained, a line representing the received signals can be created, similar to the single node approach. The center of the line arriving at the virtual array is considered as the origin of the coordinate system, denoted as O. To obtain a position estimate of a transmitter it is necessary to calculate the angle ϕ. The relationship between θ and ϕ is given by

$$\phi = -\frac{1}{\theta}. \tag{25}$$

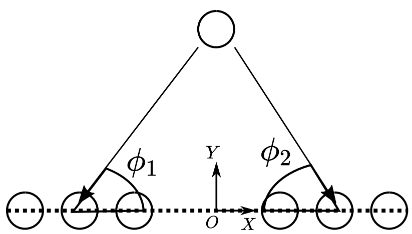

Fig. 5. Node localization via cooperative virtual arrays

Following the coordinate system shown in Figure 5, the signal received at virtual arrays Rx_1 and Rx_2 can be written as

$$y = \tan(\phi_1)x - \tan(\phi_1)x_{Rx_1}, \tag{26}$$

$$y = \tan(\phi_2)x - \tan(\phi_2)x_{Rx_2}, \tag{27}$$

where x_{Rx_1} and x_{Rx_2} are the position of virtual arrays Rx_1 and Rx_2 on the X axis.

The position of the transmitter Tx can be estimated by calculating the point where Eqs. (26) and (27) meet

$$x = \frac{\tan(\phi_1)x_{Rx_1} - \tan(\phi_2)x_{Rx_2}}{\tan(\phi_1) - \tan(\phi_2)}, \tag{28}$$

$$y = \frac{\tan(\phi_1)\tan(\phi_2)\left(x_{Rx_2} - x_{Rx_1}\right)}{\tan(\phi_2) - \tan(\phi_1)}. \tag{29}$$

VI. Simulation Results

A. Single Node Localization Performance

In the first set of simulations the performance of the proposed single node localization method is studied with respect to the SNR of the received signal. The transmitting node equidistant from the receiving nodes and the receiving nodes are equidistant from each other. The distance between the transmitting and receiving nodes is 10 m. $N = 100$ snapshots are for the position estimation. The scenario is detailed in Figure 6.

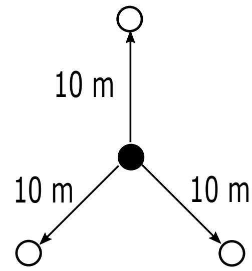

Fig. 6. Simulation scenario

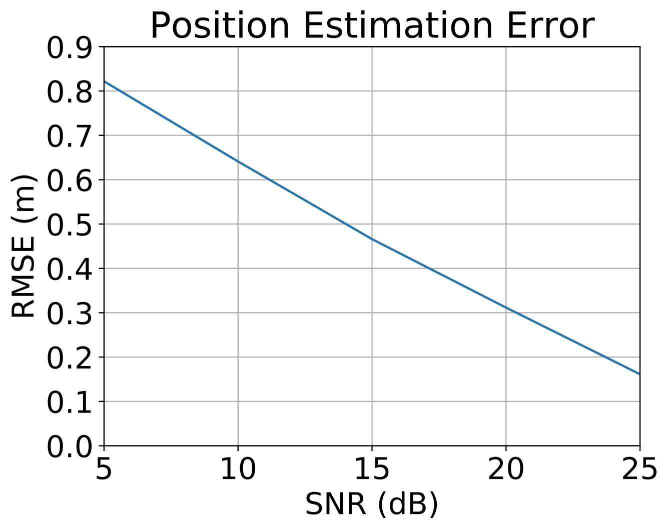

Fig. 7. Location error for the first scenario

Figure 7 presents the effects of the SNR on the performance of the proposed location method. Being perfectly centered around the receiving nodes allow for estimation errors bellow 1 meter for the entire SNR range of the simulation. Thus, in such an ideal case, errors in direction of arrival estimation do not have a great impact on positioning estimation.

To understand the performance of the proposed method under less than ideal conditions, the localized node was placed non centered with respect to the receiving nodes. Figure 8 presents the node placement for this set of simulations.

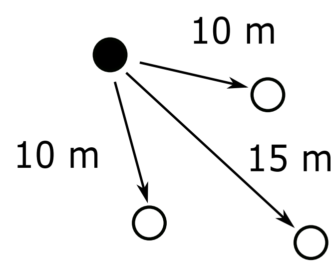

Fig. 8. Illustration of second simulation scenario

Figure 9 highlights how the error is affected by the position of the receiving nodes. Here, sub meters accuracy can only be achieved at high SNRs. When the receiving nodes are all located within a single sector, direction of arrival estimation errors result in larger positioning estimation bias.

B. Cooperative Virtual Array Localization Performance

To study the behavior of the proposed cooperative virtual array based technique we consider a complete network with an area of 100×100 m. Here, we consider that densely packed node islands are spread across the network, such as multiple BANs in a public environment. Here, enough node islands are

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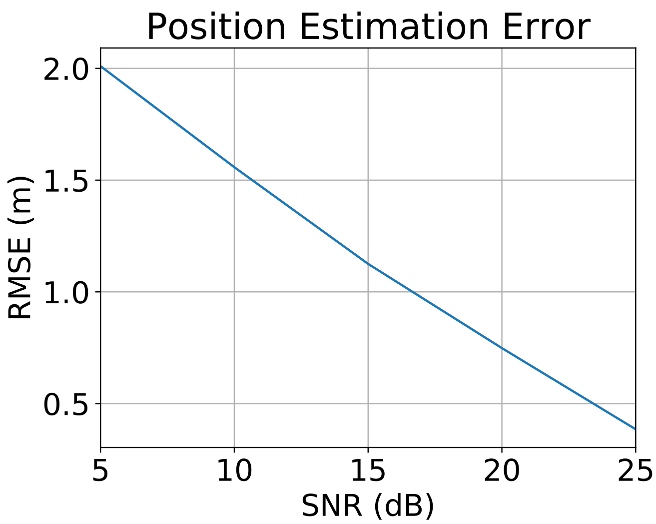

Fig. 9. Location error for the second scenario

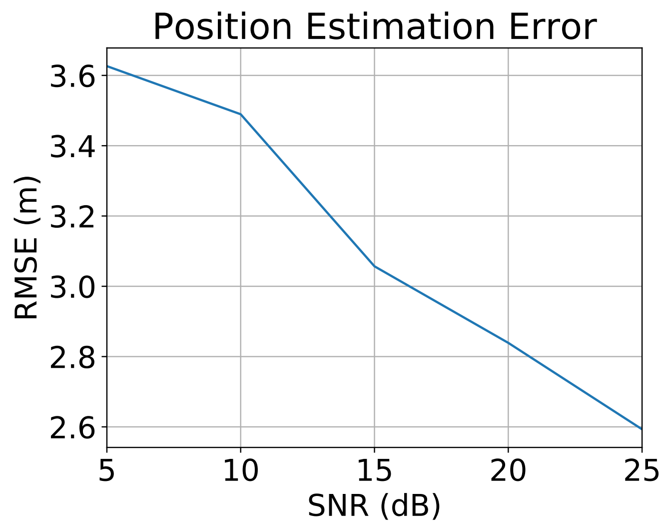

Fig. 10. Location error for full network using the cooperative virtual array method

present to guarantee that every island has a neighbor island within 3 m with probability 0.98. The amount of islands can be obtained by

$$P = (1 - \mathrm{e}^{-d\pi r^2})^n, \tag{30}$$

where d is the island density in the area, r is the distance where islands must have at least one neighbor island and n is the number of islands in the network. For this simulation, the number of islands used, according to Eq. (30), is 26. Each island is assumed to have three nodes. Here, three anchor nodes with known locations are used as reference for the remaining nodes to extract their location estimation from.

Figure 10 shows the location error averaged across the entire network. Here, another source of error is present, as the location errors will propagate across the network with each localization being made with respect to a previous one. However, with high enough SNRs it is still possible to achieve estimations with an average accuracy of 3 m, which might be sufficient for applications such as indoor positioning.

VII. Conclusion

This work presented a direction of arrival based localization approaches for IOT networks. For single node position estimation, direction of arrival estimation is done by means of a crossed dipole antenna. With prior knowledge of transmission polarization an estimate of the direction of arrival of a received signal can be obtained by analyzing the ratio of the power received at the different antenna polarization outputs. Another localization method based on using cooperating nodes to form virtual antenna arrays was also presented. The cooperative method can be used in cases of nodes with multiple close neighbors, such as multiple wearable devices on a person. The proposed virtual array method does not require dual polarization receivers or the polarization of the transmitted signal to be known. The performance of the proposed methods was analyzed by means of numerical simulations. Results are shown to stay within 2 m of precision for the single node, dual polarization method when a single node position is measured.

Acknowledgments

The research leading to the results reported in this work has received funding from the Knowledge Foundation in the framework of SafeSmart ”Safety of Connected Intelligent Vehicles in Smart Cities” Synergy project (2019– 2023), Swedish Foundation for Strategic Research (SSF) in the framework of Strategic Mobility Program (2019-2020) and the ELLIIT Strategic Research Network.

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