Network-Based Anti-Theft Alert System Using Dynamic Hybrid TOA/AOA Algorithm

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Abstract —To reduce the theft rate of smart phones, laptops and tablets in public, this paper proposes a novel network based anti-theft alert system using a dynamic hybrid time of arrival (TOA)/angle of arrival (AOA) algorithm. Specifically, the statistic weights of the results produced by the TOA and AOA methods are dynamically varied according to the signal propagation environment. In this way the combined result can be as accurate as possible regardless of the environment. The feasibility and advantages of this hybrid TOA/AOA algorithm are verified by numerical simulations. Moreover, the implementation proposal, several practical issues, and the social impacts of the system are elaborated and analysed in details.

Index Terms—Wireless location, asset tracking, anti-theft, hybrid TOA/AOA, dynamical adjustment

I. Introduction

Theft rate in the UK has remained at a relatively high level for years [1]. This causes a series of social problems and degrades the well-being of law-abiding citizens [2]. Also, with the popularisation of smart phones, laptops, and tablets, larceny encounters new situations and focuses on these electronic devices in public, especially in cafes, libraries and train stations [3], [4]. To reduce the theft rate and improve public security legislation should be improved, and up-to-date technical progresses to prevent crime employed [5]. There is substantial evidence to show that a newly introduced technique can eradicate or significantly reduce a specific kind of crime [6]. Therefore, to reduce the theft rate of smart phones, laptops and tablets in public, this papers proposes a novel network based anti-theft alert system using a dynamic hybrid time of arrival (TOA)/angle of arrival (AOA) algorithm. The structure and principle of this anti-theft alert system are simple, but useful. Compared to other location finding techniques, the dynamic hybrid TOA/AOA algorithm is self-adapting and thereby has a high accuracy regardless of the signal propagation environment [7]. Meanwhile cost analysis shows it is economical to implement this system, and has significant social impacts on crime control.

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The rest of this paper is organised as follows. In Section II, the system model is presented and explained. Then, the dynamic hybrid TOA/AOA algorithm is proposed in Section III. To verify the feasibility and the advantages of the system, numerical simulations are carried out, and the results are discussed in Section IV. A number of implementation related issues are found in Section V, whilst the social impacts of this anti-theft alert system are critically analysed in Section VI. Finally, this paper is concluded in Section VII.

II. System Model

In this paper, we constrain our discussion to a two dimension Cartesian coordinate system, i.e. only two coordinates are required in order to uniquely determine the location of an object. Therefore, we denote the real-time location of the tracked asset as $L_t = (x_t; y_t)$ Also, we define an alert threshold distance r_{th}. An alert signal will be sent if the condition below is met

$$\left(x_t - x_{t_0}\right)^2 + \left(y_t - y_{t_0}\right)^2 > r_{th}^2 \tag{1}$$

where x_{t_0} and y_{t_0} represent the initial coordinates of the tracked object and are assumed to be known.

From (1), it is clear that in order to prevent theft of the tracked object, it is necessary to estimate x_t and y_t accurately in real time. There are two methods; termed TOA and AOA, that are able to do so.

A. Measurement of Time of Arrival

The most direct and easiest way to determine the parameters above is to deploy at least three base antennas and measure the distances between the tracked object and these antennas [8]. This is referred to as the TOA method and can be illustrated in Fig. 1. As long as r_1, r_2 and r_3 can be estimated, then because the location coordinates of all three antennas are known, the tracked object is mathematically tractable. This method is more effective and accurate when these base antennas are surrounded by many scatters [9]. A number of techniques focusing on information extraction, and that are also able to determine the transmission distances have already been proposed and verified to be effective [10]–[13]. Therefore, once r_1, r_2 and r_3 have been estimated, with the estimated results are denoted as $\hat{r}_1^2$, $\hat{r}_2^2$ and $\hat{r}_3^2$, we have [9]

$$\begin{aligned}(x_1 - x_t)^2 + (y_1 - y_t)^2 &= \hat{r}_1^2 \\ (x_2 - x_t)^2 + (y_2 - y_t)^2 &= \hat{r}_2^2 \\ (x_3 - x_t)^2 + (y_3 - y_t)^2 &= \hat{r}_3^2\end{aligned} \tag{2}$$

where x_j and y_j are the corresponding coordinates of the jth antenna, given $j \in \{1,2,3\}$.

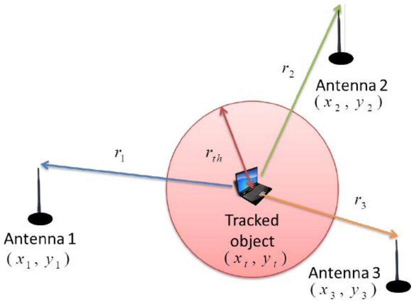

Fig. 1. Illustration of the location finding system using the TOA method

Reorganizing (2) in terms of matrices yields

$$\begin{bmatrix} 2x_1 - 2x_2 & 2y_1 - 2y_2 \\ 2x_1 - 2x_3 & 2y_1 - 2y_3 \end{bmatrix} \begin{bmatrix} x_t \\ y_t \end{bmatrix} = \begin{bmatrix} (\hat{r}_2^2 - \hat{r}_1^2) + (x_1^2 - x_2^2) + (y_1^2 - y_2^2) \\ (\hat{r}_3^2 - \hat{r}_1^2) + (x_1^2 - x_3^2) + (y_1^2 - y_3^2) \end{bmatrix} \tag{3}$$

Without loss of generality, we can generalise the situation when multiple base antennas (the number of antennas $M \geq 3$) are involved and obtain the equation set below

$$\mathbf{A}_{TOA}\mathbf{L}_t = \mathbf{B}_{TOA} \tag{4}$$

where

$$\mathbf{A}_{TOA} = \begin{bmatrix} 2x_1 - 2x_2 & 2y_1 - 2y_2 \\ 2x_1 - 2x_3 & 2y_1 - 2y_3 \\ \vdots & \vdots \\ 2x_1 - 2x_M & 2y_1 - 2y_M \end{bmatrix} \tag{5}$$

$$\mathbf{L}_t = \begin{bmatrix} x_t \\ y_t \end{bmatrix} \tag{6}$$

$$\mathbf{B}_{TOA} = \begin{bmatrix} (\hat{r}_2^2 - \hat{r}_1^2) + (x_1^2 - x_2^2) + (y_1^2 - y_2^2) \\ (\hat{r}_3^2 - \hat{r}_1^2) + (x_1^2 - x_3^2) + (y_1^2 - y_3^2) \\ \vdots \\ (\hat{r}_M^2 - \hat{r}_1^2) + (x_1^2 - x_M^2) + (y_1^2 - y_M^2) \end{bmatrix} \tag{7}$$

$\mathbf{L}_t$ is estimated using the maximum likelihood (ML) technique, and the result is given by [14], [15]

$$\hat{\mathbf{L}}_{t-TOA} = \begin{bmatrix} \hat{x}_{t-TOA} \\ \hat{y}_{t-TOA} \end{bmatrix} = \left(\mathbf{A}_{TOA}^T \mathbf{A}_{TOA}\right)^{-1} \mathbf{A}_{TOA}^T \mathbf{B}_{TOA} \tag{8}$$

where $(\cdot)^T$ represents the transpose of a matrix; $(\cdot)^{-1}$ represents the inversion of a matrix.

B. Measurement of Angle of Arrival

Another method to estimate $\mathbf{L}_t$ is called the AOA method. The advantage of the AOA method over the TOA method is that the minimum number of antenna required is one, instead of three [16], [17]. On the other hand, more complex data transmission and extraction protocols are required, since not only transmission distance, but also the angle of transmission needs to be measured [18]. Moreover, the AOA method is effective and accurate only if a light-of-sight path between the tracked object and the base antenna can be constructed [9]. A typical system employing the AOA method with a single base antenna is illustrated in Fig. 2.

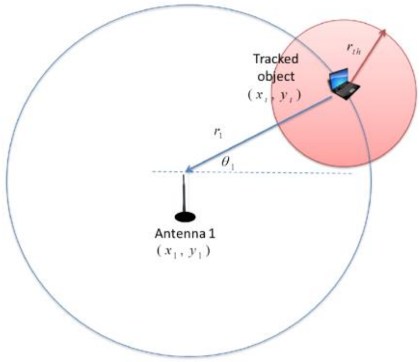

Fig. 2. Illustration of the location finding system using the AOA method.

From Fig. 2, we have

$$\begin{bmatrix} x_t \\ y_t \end{bmatrix} = \begin{bmatrix} x_1 + \hat{r}_1 \cos\hat{\theta}_1 \\ y_1 + \hat{r}_1 \sin\hat{\theta}_1 \end{bmatrix} \tag{9}$$

We generalize (9) to a general case when multiple base antennas (the number of antennas $M \geq 1$ are involved and obtain [9]

$$\mathbf{A}_{AOA}\mathbf{L}_t = \mathbf{B}_{AOA} \tag{10}$$

where

$$\mathbf{A}_{AOA} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ \hline 1 & 0 \\ 0 & 1 \\ \hline \vdots & \vdots \\ \hline 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{11}$$

$$\mathbf{B}_{AOA} = \begin{bmatrix} x_1 + r_1 \cos\theta_1 \\ y_1 + r_1 \sin\theta_1 \\ \hline x_2 + r_1 \cos\theta_2 \\ y_2 + r_1 \sin\theta_2 \\ \hline \vdots \\ x_M + r_1 \cos\theta_M \\ y_M + r_1 \sin\theta_M \end{bmatrix} \tag{12}$$

As previously, we can estimate $\mathbf{L}_t$ by the ML technique and the result is produced by [19]

$$\hat{\mathbf{L}}_{t-AOA} = \begin{bmatrix} \hat{x}_{t-AOA} \\ \hat{y}_{t-AOA} \end{bmatrix} = \left(\mathbf{A}_{AOA}^T \mathbf{A}_{TOA}\right)^{-1} \mathbf{A}_{AOA}^T \mathbf{B}_{AOA} \tag{13}$$

III. DYNAMIC HYBRID TOA/AOA ALGORITHM

From the previous section, it is obvious that the accuracies of the TOA and AOA methods depend on the communication environment. Therefore, if the communication environment is time-varying, the priority of the TOA and AOA methods will be varied accordingly [9]. To maintain the overall accuracy, we combine the results produced by both the TOA and AOA methods and dynamically adjust their statistic weights according to the communication environment. A similar algorithm has been proposed and works well for real-time measurement [20]–[22], We can apply this method to the location finding scenario. Specifically, we construct the combined estimated result by

$$\hat{\mathbf{L}}_t = \begin{bmatrix} \hat{x}_t \\ \hat{y}_t \end{bmatrix} = \frac{w_{TOA}\hat{\mathbf{L}}_{t-TOA} + w_{AOA}\hat{\mathbf{L}}_{t-AOA}}{w_{TOA} + w_{AOA}} \tag{14}$$

where w_{TOA} and w_{AOA} are statistic weights of TOA and AOA methods respectively and their values are dynamically varied according to the communication environment. Considering a system in a real-time manner, we have the recurrence relation below for the variation of w_{TOA} and w_{AOA}:

$$w_Z(n) = G_Z(n-1)w_Z(n-1) \tag{15}$$

where $Z \in \{TOA, AOA\}$; n represents the estimated instant; $G_Z(n-1)$ is the self-adapting gain dependent on the communication environment at instant $(n-1)$.

Without loss of generality, and assuming $w_Z(0) = 1$ and $G_Z(0) = G_Z(1) = 1$, we have

$$w_Z(n) = w_Z(0)\prod_{i=0}^{n-1} G_Z(i) = \prod_{i=0}^{n-1} G_Z(i) \tag{16}$$

Now, we focus on how to adjust $G_Z(i)$ so that an accurate combined estimated result will be given. In order to design a robust adjustment mechanism, we first assume that the estimated time interval of the base antennas is small enough so that the tracked object cannot have a significant displacement between two estimated instants. Also, perfect synchronization among all communication nodes in this small tracking network is assumed as well. Following this logic, we can use the coordinates' variation within one estimation interval to determine the accuracy of the TOA and AOA method. That is, if the estimated coordinates between two time instants are relatively stable, we assume the corresponding method is accurate. Therefore, we can vary the two self-adapting gains at the ith estimated instant by

$$G_{TOA}(i) = \frac{\left|\hat{L}_{t-AOA}(i) - \hat{L}_{t-AOA}(i-1)\right|}{\left|\hat{L}_{t-TOA}(i) - \hat{L}_{t-TOA}(i-1)\right|} \tag{17}$$

and

$$G_{AOA}(i) = \frac{1}{G_{TOA}(i)} = \frac{\left|\hat{L}_{t-TOA}(i) - \hat{L}_{t-TOA}(i-1)\right|}{\left|\hat{L}_{t-AOA}(i) - \hat{L}_{t-AOA}(i-1)\right|} \tag{18}$$

Finally, substituting (16), (17) and (18) into (14) yields the combined estimated result at the nth instant

$$\hat{L}_t(n) = \frac{\left(\prod_{i=1}^{n-1} G_{TOA}^2(i)\right)\hat{L}_{t-TOA}(n) + \hat{L}_{t-AOA}(n)}{\left(\prod_{i=1}^{n-1} G_{TOA}^2(i)\right) + 1} \tag{19}$$

IV. NUMERICAL RESULTS AND DISCUSSION

A. Simulation Setup

Assume a static object located at (xt0; yt0) = (0; 0) and four base antennas located at (x_1; y_1) = (3; 6), (x_2; $y2$) = (4; 2), (x_3; y_3) = (−5; 1) and (x_4; y_4) = (−4; −3) respectively. The measured distances $\hat{r}_j$ and angles $\hat{\theta}_j$, $j \in \{1,2,3,4\}$ are random variables due to the stochastic properties of the communication environment [9]. To generate both variables, we define four Gaussian distributed variables for the jth antenna as

$$\tilde{x}_j, \hat{x}_j \sim N\left(x_{t_0}, \sigma^2\right) \tag{20}$$

and

$$\tilde{y}_j, \hat{y}_j \sim N\left(y_{t_0}, \sigma^2\right) \tag{21}$$

where σ is the standard deviation of these four variables. Without loss of generality, we set $\sigma \in \{0.05, 0.1, 0.2\}$ in the following simulations, so that the effects of different σ on the estimation accuracy can also be shown.

Therefore, we can generate the random measured distances $\hat{r}_j$ and angles $\hat{\theta}_j$ by

$$\hat{r}_j = \sqrt{(\tilde{x}_j - x_j)^2 + (\tilde{y}_j - y_j)^2} \tag{22}$$

and

$$\hat{\theta}_j = \begin{cases} \pi + \arctan\dfrac{\hat{y}_j - y_j}{\hat{x}_j - x_j}, & x_j > 0,\ y_j > 0 \\ 2\pi - \arctan\dfrac{\hat{y}_j - y_j}{\hat{x}_j - x_j}, & x_j \le 0,\ y_j > 0 \\ \arctan\dfrac{\hat{y}_j - y_j}{\hat{x}_j - x_j}, & x_j \le 0,\ y_j \le 0 \\ \pi - \arctan\dfrac{\hat{y}_j - y_j}{\hat{x}_j - x_j}, & x_j > 0,\ y_j \le 0 \end{cases} \tag{23}$$

N.B. $\hat{r}_j$ and $\hat{\theta}_j$ are statistically independent when generated in simulations, since $\tilde{x}_j$, $\hat{x}_j$, $\tilde{y}_j$, and $\hat{y}_j$ are statistically independent.

Because now we have

$$\mathbf{L}_t = \mathbf{L}_{t_0} = \begin{bmatrix} x_{t_0} \\ y_{t_0} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{24}$$

we can define the absolute estimation error by

$$\delta = \left|\mathbf{L}_t - \hat{\mathbf{L}}_t\right| = \left|\hat{\mathbf{L}}_t\right| \tag{25}$$

Also, because the tracked object is static in this case, the false alarm rate, as an important performance measurement, is defined as

$$P_e = \mathrm{P}\left(\hat{x}_t^2 + \hat{y}_t^2 > r_{th}^2\right) \tag{26}$$

In the following simulations we examine both P_e and δ. We will look at the number of estimation instants for different σ and employ them as a metric to evaluate the feasibility, performance, and reliability of the proposed anti-theft alert system. To model the false alert event, we set the alert threshold distance r_{th} = 0.5.

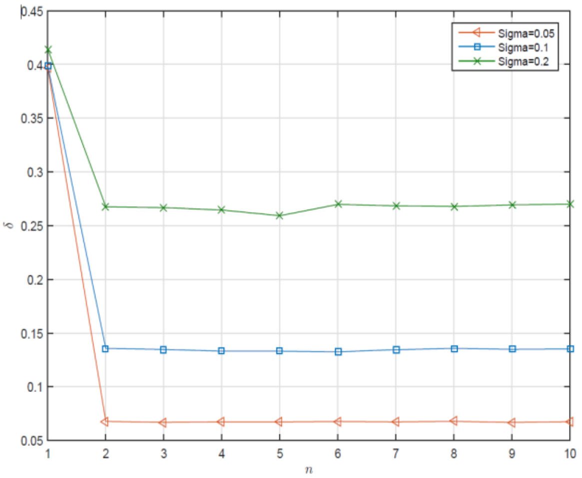

Fig. 3. Relation between δ and n with different $\sigma \in \{0.05, 0.1, 0.2\}$

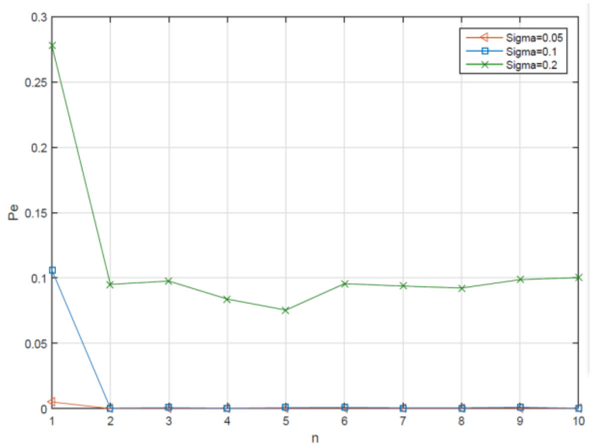

Fig. 4. Relation between P_e and n with different $\sigma \in \{0.05, 0.1, 0.2\}$

B. *Simulation Results and Discussion*

By Monte Carlo simulation, the relation between δ and n with different σ is illustrated in Fig. 3. Similarly, the relation between P_e and n with different σ is illustrated in Fig. 4. Both figures show us that increasing the number of estimation instants will yield a lower estimation error as well as a lower false alarm rate. They verify our analysis and the feasibility of the proposed system. However, increasing the number of estimated instants cannot reduce both to infinitesimal, rather, both δ and P_e plateau at a certain level, which is related to the communication environment. As for the effects of σ; a large δ will yield a worse performance of the system in terms of estimation error and false alarm rate, as expected. This is because the standard deviation σ indicates the degree of stability of the communication environment.

V. Implementation

A. *Implementation Proposal*

To aid the implement of this anti-theft alert system, a flowchart describing how this system works is constructed. Borrowing the framework from some similar applications [21]–[24], the flowchart is illustrated in Fig. 5. This flowchart is explained step by step below.

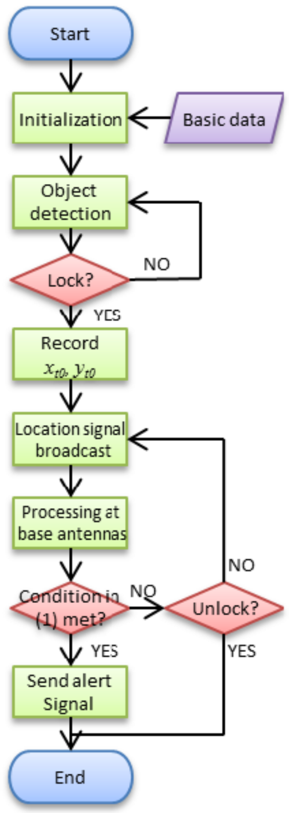

Fig. 5. Flowchart of the anti-theft alert system

1) Initialization: input a series of basic data, including the initial coordinates of base antennas and the initial values of $w_Z(0)$, $G_Z(0)$ and $G_Z(1)$ etc.

2) Object detection: detect whether there is an object which may need to be protected in the network.

3) Lock?: check whether a protection application is sent by the object.

4) Record x_{t_0}, y_{t_0}: detect the initial coordinates of the tracked object as a reference point. Note, here we assume that x_{t_0} and y_{t_0} can be perfectly obtained.

5) Location signal broadcast: the tracked object broadcasts its current location to all base antennas in a real time manner.

6) Processing at base antennas: the location signal is processed at the base antennas and the real-time location is estimated by the dynamic hybrid TOA/AOA algorithm as described in the previous section.

7) Condition in (1) met?: Check whether the location of the tracked object is outside the circle located at the origin with a radius r_{th}.

8) Send alert signal: if the condition in (1) has been met, an alert signal will be sent and a series of corresponding responses will be carried out to prevent the tracked object from theft.

9) Unlock?: check whether the protection status needs to be released.

B. *Cost Analysis of Implementation*

The cost of implementation consists of three parts, which are research cost, installation cost, and administration cost. We will analyse both as follows.

1) Research cost: The research cost comes from the research procedure, i.e. the process from the proposal of an idea, until commercialisation. The research cost is estimated and summarised in Table I.

2) Installation cost: The installation cost comes from the installation of this proposed system in a public domain, e.g. a cafe, a library, a restaurant. This cost has been estimated and summarised in Table II.

3) Administration cost: After the installation of the anti-theft alert system, an extra cost for administration will be required for each month. It is listed in Table III.

TABLE I. SUMMARY OF RESEARCH COST

Items	Costs in GBP
Theoretical advanced research	800
Patent application	1800
Hardware prototype development	1400
Prototype tests	800
Circuit design and print	400
Hardware industrial design	1200
Software design	800
Software tests	400
Compatibility tests	1200
Field tests	1500
Legality and ethics relevant issues	500
Commercialization	4000
In total	14800

TABLE II. SUMMARY OF INSTALLATION COST

Items	Costs in GBP
Antenna installation	400
Link installation	600
Field tests	150
Labor	1000
In total	2150

TABLE III. SUMMARY OF INSTALLATION COST

Items	Costs per month in GBP
Maintenance	50
Extra electricity	20
Extra communication traffic	50
Security update	20
Other service	30
In total	170

VI. SOCIAL IMPACTS

As the technical details and implementation-related issues have been analysed and presented, we will analyse the social impacts of this proposed system in this section. The analysis will be categorised into a few sections.

A. *Crime Prevention*

As explained in Section I, most crimes targeting electronic assets occur in public. The proposed system can effectively track the protected devices and thus is able to prevent this kind of crime. However, this paper notes that frequent security updates of this system would be required, to prevent a thief finding a way to interfere with the anti-theft alert system, e.g. jamming and impersonation attacks [25], [26]. Also, the response to the theft alert sent by this anti-theft alert system is worth investigating in order to find the best way to prevent the tracked item being stolen.

As long as these problems can be solved comprehensively, the living quality of people can be significantly improved by this anti-theft alert system. They will not need to carry their electronic devices, e.g. a laptop or mobile phone with them when they leave the public place for a short period e.g. to use the toilet. Moreover, a more secure public place can be provided; benefiting the whole society.

B. *Environment*

Although this system has no obvious negative environmental impact, we still need to examine the electromagnetic radiation produced by this system carefully. Abundant radiations due to the large transmit power from the product devices could be harmful to health and thus a series of strict field tests need to be carried out to ensure the level of radiation lies below a certain threshold [27].

C. *Privacy*

Because the proposed system is able to track the physical location of an electronic device, it is also possible that without secure administrations and relevant legislations, this system will be used for illegal purposes [11], [28]. In order to mitigate these negative effects, we should consider the legality and ethically relevant issues when implementing it. Anonymous protection could be adopted, by which the anti-theft alert system can protect an item without requiring any identity information.

D. *Economy*

As expected, the implementation and the maintenance of this system will bring an extra cost for the companies that adopt it. Therefore, whether there is a promising market for this proposed system is still questionable. Also, how to reduce the cost of implementation and enhance the reliability of the system are worth investigating. Only with a comprehensive implementation plan will this anti-theft alert system be economically feasible.

VII. CONCLUSIONS

This paper has proposed a novel network-based anti-theft alert system in order to reduce the theft rate of small electronic devices such as smart phones, laptops, and tablets in public. This proposed system adopts a dynamic hybrid TOA/AOA algorithm so that its tracking accuracy will not be degraded regardless of different wireless propagation environments. The analysis has been verified by numerical simulations. This paper has addressed the implementation issues and analysed the implementation cost. Moreover, the social impacts of this antitheft alert system were analysed in four aspects. In conclusion, based on the analysis and simulations presented above, the technical feasibility of this system has been proven in an ideal environment. However, in order to obtain the first prototype of this system, the practical and financial issues need to be considered further.

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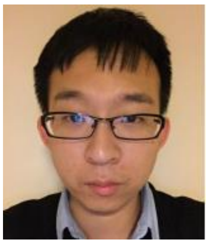

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