Adaptive Linearized Methods for Tracking a Moving Telemetry Capsule

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***Abstract*— In this paper, we discuss system and method of determining the real-time location of an omni-directional diagnostic radio frequency (RF) system while the object (transmitter) is moving freely inside an inaccessible organ. A specific application to the human gastrointestinal (GI) organ is presented, showing the importance of the method in accessing a specific site for drug administration or for extracting fluid or tissue samples for biopsy and similar medical investigations. For practical purposes, omnidirectional antenna on the transmitter at 433MHz, normalized transmitter power 1W was modeled for simplicity, and Es/No = 20dB (corresponding to the linear region of the target transceiver). A brief discussion of how the original analogue signals, after conversion to voltage, was adapted for position tracking. In the tracking algorithm, we employed a path loss scenario based on the popular log-normal model to simulate the effects of organs on signal quality between transmitter and receiver at various distances.**

***Index Terms*— GastroIntestinal Tract, Telemetry Capsule, Trilateration, Short Range device (SRD), Object tracking.**

I. INTRODUCTION

Telemedicine is often defined as medicine at a distance – a service with the potential to have a favorable impact on the access, quality, and cost of health care. Wireless communication is therefore an important technology enabler for telemedicine, offering the potential for both patient mobility and ubiquity of service. In particular, radio communication has been and will continue to be the dominant technique for wireless telemedicine [1]. Although the alternatives to radio waves have been used in telemedicine, they are either limited to line-of-sight environments, or suffer from extremely low bandwidths e.g. ultrasonic waves at 1MHz [2].

The wider definition of telemedicine covers all uses of communication technology, including data links with diverse devices, such as sensors, actuators (e.g bladder, or muscle stimulators), and controllers/processors. In this paper, a unique problem of tracking the real-time positions of a diagnostic capsule in the GI tract will be considered. The final solution is a fully developed estimation algorithm that utilizes radio frequency signals or the received signal strength indicator (RSSI) [3] output of an array of transceivers converted to voltage. We employed a modified form of the traditional radio-map based deterministic model that requires an estimate of initial position vector.

Fig. 1 shows the basic building blocks of the entire signal manipulation process from transmitter to receiver through the channel, subject to various path loss variables, some of which are modeled into distance d, path loss index η, channel noise, etc. This forms the basis for data collection stage necessary for tracking as applied to a capsule inside the human GI tract using the strength of RF signal obtained at some fixed position sensors positioned on the surface of the abdomen. The RSSI relates, albeit roughly, the distance between the transmitter to the receiver and can be used to tract the motion of the transmitter if more than one receiver is present.

In our approach, the moving object is capable of transmitting RF signals at 433MHz and the externally placed receivers are able to receive the signal. This procedure of signal transmission and received signal power detection is repeated at intervals in order to collect a set of object position data. At the end, such position data are analyzed on a PC running custom triangulation algorithms to determine the real-time positions of the moving object.

As presented in this paper, object positioning was implemented by using received signal strength (RSS). RSS is a measure of the power received by a radio receiver from a radio transmitter and provides information as to the proximity of the transmitter. Indeed, RSSI is location dependent as it is affected by factors such as distance from the transmitter and attenuation due to medium of propagation and other barriers. The final goal in the use of the transmitter and receiver is to transmit a signal from the object to some receivers placed on the abdomen, and to have those receivers return the signal strength in order to determine the correct location of the object. The

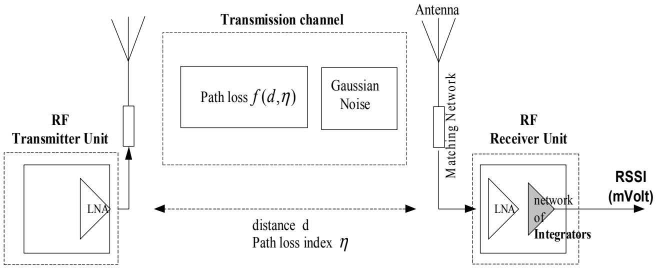

Fig. 1. Block diagram of RF system (Transmission, Channel and Reception)

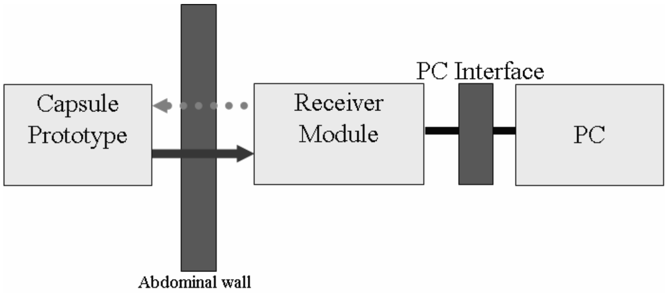

Fig .2.Block diagram of RF diagnostic system

data being sent across from transmitter to receiver is, in itself, unimportant. The significant information is the RSSI. The block diagram of the total concept is as illustrated in Fig. 2. The receivers are capable of reading the level of the signal and output it in a form that can easily be translated into a form that the computer can understand.

Fig. 3 shows the pictorial view of the method employed in the entire process from data capture to data analysis. Fixed position sensors are situated as shown and are connected via a 50 Ω coaxial cable to the transceivers/microcontroller board where intermediate data are stored before uploading to the PC. Custom algorithm runs on the PC to produce the real-time position data. The sensors are arranged on the abdomen with the aid of receiver belts which are elastic and extendable. The PC interface is hung on the patient's waist belt during data collection stages. It connects to the PC via an RS232 connector in order to download stored data to the PC running custom algorithm to produce the real-time position information at the end of data collection.

A. *Factors affecting the receivers variability*

Generally speaking, the parameters that affect the received signal strength between a pair of communicating nodes which affects its suitability for precision tracking applications are as follows:

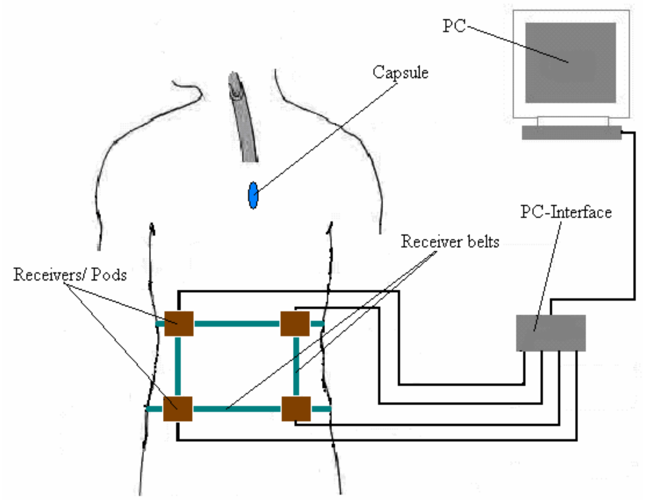

Fig. 3 Capsule tracking with RSSI output.

1) Transmitter variability: Different transmitters behave differently even when they are configured exactly in the same way. In practice, this means that when a transmitter is configured to send packets at a power level of d dBm then the transmitter will send these packets at a power level that is very close to d dBm but not necessarily exactly equal to d dBm. This can alter the RSSI and thus it can lead to inaccurate distance estimation. (dBm is commonly used in RF measurements, 0 dBm is defined as 1 mW of RF signal dissipated in a 50-Ω resistive load)

2) Receiver variability: The sensitivity of the receivers across different radio chips is different. In practice, this means that the RSSI value recorded at different receivers can be different even when all the other parameters that affect the received signal strength are kept constant.

3) Antenna orientation: Each antenna has its own radiation pattern that is not uniform. In practice, this means that the RSSI value recorded at the receiver for a given pair of communicating nodes and for a given distance between them varies as the pairwise antenna orientations of the transmitter and the receiver are changed.

4) Multi-path fading and shadowing in the RF channel:
In indoor environments for example, the transmitted signals get reflected after hitting on the walls and/or on other objects in the room such as furniture. Both the original signal and the reflected signal reach the receiver almost at the same time since they both travel at the speed of light. As a result of this, the receiver is not able to distinguish the two signals and it measures the received signal strength for both of them.

The most widely used signal propagation model is the log-normal shadowing model [4] which is generally modeled by:

$$\text{RSSI (d)} = P_T - P_L(d_0) - 10\eta \log_{10} \frac{d}{d_0} + X_\sigma [4] \qquad (1)$$

where, P_T is the transmit power, $P_L(d_0)$ is the path loss for a reference distance d_0 (dB) at 1m distance (30dB) [5].
η is the path loss exponent and
X_σ is a Gaussian random variable with zero mean and σ^2 variance, that models the random variation of the RSSI value.
d = distance between transmitter and receiver.

For application in the GI tract however, traditional methods of radio localization based on time and/or angle based methods (Time of Arrival, Time Difference of Arrival and Angle of Arrival) are not feasible due to the dense multi-path characteristics [2]. Therefore, to accurately determine the position of an object in the GI tract for example, simultaneous

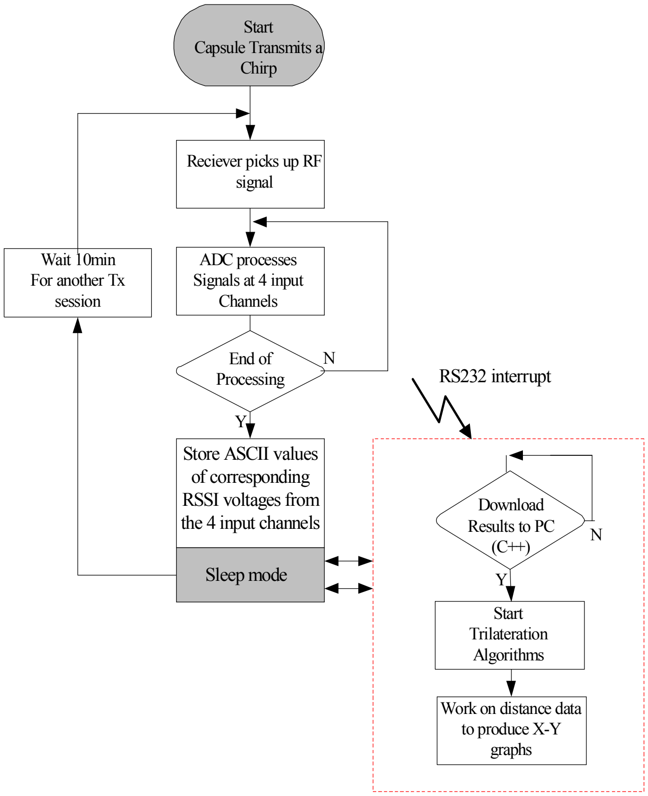

Fig.4 Flow chart of sequence of data events.

RSSI measurements from several access points (AP) are needed.

II. METHODS

A. Flow of Events

As shown in the flow diagram of Fig. 4, the tracking process begins when the object transmits a radio signal, usually at 433MHz (within the free Industrial, Scientific and Medical band in Europe). The externally placed receivers pick up the signal almost instantaneously and the PC interface circuit processes the input signals received at the receiver antennas one channel after the other. Consequently, the level of voltage or the receive signal strength at the receivers are a rough estimate of the proximity of the object (transmitter) relative to the receiver antennas (sensor).

At some pre-set time interval, the microprocessor (μC) enables the interface circuits to respond to incoming RF signals by sampling the input and converting the data to analog voltage corresponding to the intensity of the received RF signal at those times. These measurements are converted by the ADC to digital signals one channel after the other. The results of each conversion are stored in memory. These sequences of events are repeated for the period of test. Repeatability is achieved by programming the ADuC831μC. In the GI tract, the most reasonable time to take measurement is usually the time for transition between the duodenum and the cecum which is 8 hours to 24 hours on average after ingestion [6]. Although the total transit period can be lengthened by a delay in the colon to about 75 hours [6], depending on the state of health of the patient and also on the frequency of filling and emptying of the stomach. Table 1 shows the average transit times inside the GI tract.

TABLE I
AVERAGE TRANSIT TIMES ALONG THE GI TRACT

Feature	**Average Transit time (min)**
Oesophagus	*2*
Stomach	*36 – 65*
Small intestine	*194 – 246*
Large intestine (Colon)	*36 - 75*

B Triangulation

Triangulation [7] is usually employed to convert the proximity data from the last section into position information. Triangulation is essentially the use of the properties of triangles to calculate distances. Originally, triangulation was used for surveying and civil engineering purposes, and later in mobile networks and also for finding the range of targets for artillery strikes. [8].

Given any two reference/access points (AP1, AP2) it is possible to calculate the distance from one reference point to an object with knowledge of the angles between both references and the object and also the distance between the access points. With this amount of information, distances from the object can be computed. These distances represent the radii of circles drawn from the receivers at the specific access points to the location of the object. As shown in Fig. 5, three of such circles intersecting will provide the true position of the object in 2-D. If the distances from one access and the neighboring ones are known, it is possible to fully determine the resulting triangle and as such, the real-time location of the object. In this implementation however, we did not solve for object position based on the intersection of 3 circles, but we used the linear approximation techniques on the data received from RSSI conversion process to predict the position of the object and based on the initial prediction, the final position of the object can be computed. As discussed above, we employed the method of trilateration for the object position tracking. Indeed, this approach facilitates the implementation of fully automated real-time position measurements by eliminating the need to measure angles. Fairly accurate object positions can be computed by using initial approximate distances, also known as position vectors, and by employing a finite amount of

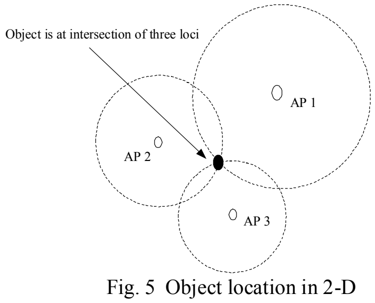

Fig. 5 Object location in 2-D

iterative least squares procedures, configured about a certain accuracy limit, i.e. 25%.

III. SOLUTION TECHNIQUE

With this approach, this positioning problem can be solved by treating the unknown coordinates of the object *R(x, y, z)* as the point of intersection of several spheres, whose centers are the locations of the externally placed sensors.

The unknown coordinates of the object is denoted as *x, y, z.* (from any arbitrary reference origin (0, 0))

If the 3 coordinates *x, y, z* are considered, the objects exact distance $\vec{r}_i$ (radii) is calculated from the approximate values and the coordinates of the sensors (x_i, y_i, z_i) as:

$$\vec{r}_i = \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} \qquad (2)$$

Determining these unknown coordinates is the first main task in this section.

Of course, the known exact distances between the object and the sensors, r_i, are the radii of the individual spheres. The equation for any of these spheres is shown above or by:

$$\vec{r}_i^{\,2} = (x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2 \qquad (3).$$

The point of intersection of the surfaces of *n* of these spheres is obtained by letting *i* = 1, 2, 3,..*n*, and solving the resulting *n* non-linear equations simultaneously to eliminate two coordinates. This solution technique is quite involved because it produces a non-linear equation of high degree. Furthermore, since the equations are quadratic, many cases for sign changes would have to be considered.

Linearizing the system of equations will reduce the degree, and convert the problem into one of finding the point of intersection of planes which is easier to manipulate.

Therefore, by applying a linearizing technique [9] on equation (3) and subtracting x_j, y_j and z_j, we have, assuming for now, that all radii are the same, equation (3) transformed to: :

$$(x - x_j + x_j - x_i)^2 + (y - y_j + y_j - y_i)^2 + (z - z_j + z_j - z_i)^2 = r_i^2 \qquad (4)$$

with ($i = 1,2,...j-1, j+1,...,n$), using the j^th^ constraint.

So, by expanding equation (4), we get:

$$((x-x_j) - (x_i-x_j))^2 + ((y-y_j) - (y_i-y_j))^2 + ((z-z_j) - (z_i-z_j))^2 = r_i^2,$$

which after grouping terms together, yield:

$$(x-x_j)^2 - 2((x-x_j)(x_i-x_j)) + (x_i-x_j)^2 +$$
$$(y-y_j)^2 - 2((y-y_j)(y_i-y_j)) + (y_i-y_j)^2 +$$
$$(z-z_j)^2 - 2((z-z_j)(z_i-z_j)) + (z_i-z_j)^2 = r_i^2$$

Regrouping terms leads to

$$(x-x_j)(x_i-x_j) + (y-y_j)(y_i-y_j) + (z-z_j)(z_i-z_j)$$
$$= \frac{1}{2}[(x-x_j)^2 + (y-y_j)^2 + (z-z_j)^2 - r_i^2$$
$$+ (x_i-x_j)^2 + (y_i-y_j)^2 + (z_i-z_j)^2] \qquad (5)$$

$$\text{or} = \frac{1}{2}[r_j^2 - r_i^2 + d_{ij}^2] = b_{ij} \qquad (6)$$

where

$$d_{ij} = \sqrt{(x_i-x_j)^2 + (y_i-y_j)^2 + (z_i-z_j)^2} \qquad (7)$$

is the distance between sensors *i* and *j.*

Since it does not matter which constraint is selected as a linearizing tool, arbitrarily select the first constraint (*j =1*). That is, select the first sensor. Since i = 2, 3,4 (*n = 4*). This leads to a linear system of 3 (*n – 1*) equations in 3 unknowns.

From equation (5) and (6), we can summarize the linearized equations as:

$$(x-x_1)(x_2-x_1) + (y-y_1)(y_2-y_1) + (z-z_1)(z_2-z_1) =$$
$$\frac{1}{2}[r_1^2 - r_2^2 + d_{21}^2] = \mathbf{b_{21}} \qquad (8)$$
$$(x-x_1)(x_3-x_1) + (y-y_1)(y_3-y_1) + (z-z_1)(z_3-z_1) =$$
$$\frac{1}{2}[r_1^2 - r_3^2 + d_{31}^2] = \mathbf{b_{31}} \qquad (9)$$
$$(x-x_1)(x_4-x_1) + (y-y_1)(y_4-y_1) + (z-z_1)(z_4-z_1) =$$
$$\frac{1}{2}[r_1^2 - r_4^2 + d_{41}^2] = \mathbf{b_{41}}$$

(10)

The above linear system of equations can easily be written in matrix form as:

$$A\vec{x} = \vec{b} \qquad (11)$$

with

$$A = \begin{pmatrix} x_2 - x_1 & y_2 - y_1 & z_2 - z_1 \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 \\ x_4 - x_1 & y_4 - y_1 & z_4 - z_1 \end{pmatrix}$$

$$\vec{x} = \begin{pmatrix} x - x_1 \\ y - y_1 \\ z - z_1 \end{pmatrix}, \qquad \vec{b} = \begin{pmatrix} b_{21} \\ b_{31} \\ b_{41} \end{pmatrix} \qquad (12)$$

where $\vec{b}$ is directly related to r_j, r_i and the distance between sensors *i* and *j*. The linear system of equation (11) has 3 equations in 3 unknowns. Therefore, theoretically only three sensors are needed in order to determine the unique position of the object in 2D.

IV. RESULTS

The receiver hardware was calibrated in order to benchmark the results of position tracking. As shown if Fig.6 we observed that the receivers performed optimally when signal to noise ratio calculated with (Eb/No), i.e. the ratio of bit energy to noise power spectral density (Number of bits per symbol) lies within 20 – 30dB at a channel distance of = 5cm, i.e. -1dB path loss and 1W input signal strength. The bit error rate (BER) parameter is used to assess the performance of the transceiver. The BER is used here to assess the sensitivity of the transceiver over the range of Es/No values subject to the optimum path loss configuration chosen for the model. The resulting graphs of Fig. 6 show the best region for optimum performance of the test/target transceiver. Also as shown in Fig.7, the optimum power distribution for the antenna selection shows that the best region lies within 20 – 30 cm radius of the transmitter at 433 MHz.

As shown in Figs 8, 9 and 10, the objects position measurements computed from the algorithm were within an average accuracy of about 25% when compared with the corresponding model estimates.

The system employs a 3 - receiver network to pick the RSSI signals emanating from the object. The receivers are at known distances from one another. As shown in Fig. 5, the position of the object at any time t_n is the point of intersection of all loci of circles formed from radii to the object from relevant APs [2]. Of course, if the length traveled prior to this position is known, then, as shown in Fig 8, the current accumulated length L_n at capsule position P_n can be computed from the past trajectory at position P_{n-1}. This is done inside the internals of the tracking algorithm. Fig. 10 is a graph of the capsule position based on the rough estimates provided by the Linear Least Squares or the first stage of trilateration algorithm. These forms the starting point of the position coordinate refinements to be made by the Non-Linear Least squares stages to produce the final results as shown if Fig. 10 which is the final results proposed by the Non-Linear Least square iteration over the calculated values. The offset in position obtained as a result of inaccurate measurement, interference, equipment error, etc are as shown

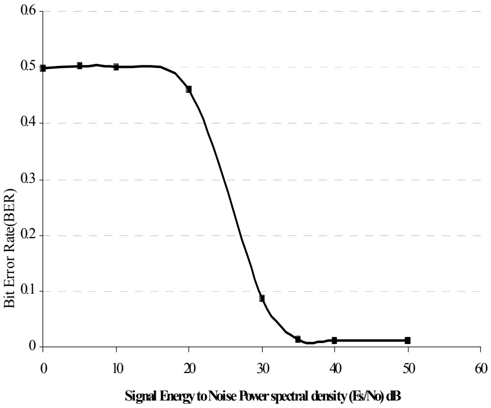

Fig.6 Receiver Es/No characteristics showing the linear region

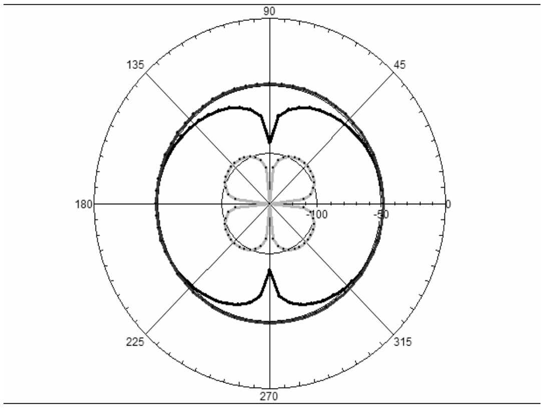

Fig.7 Antenna radiation pattern at 433 MHz

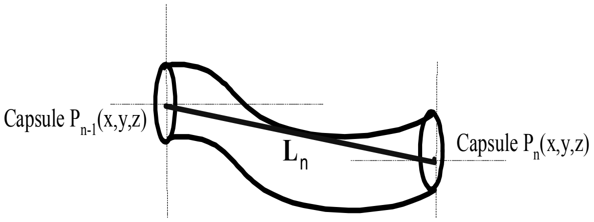

Fig. 8 Length Computation by recursive addition

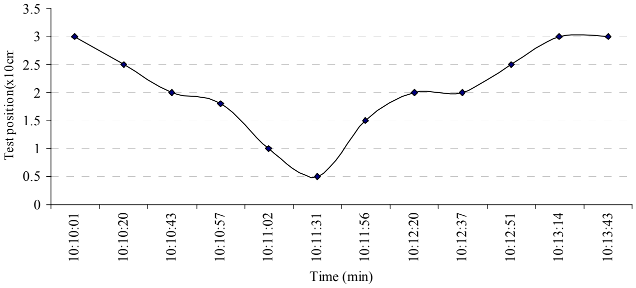

Fig. 9 Capsule Position (Estimated)

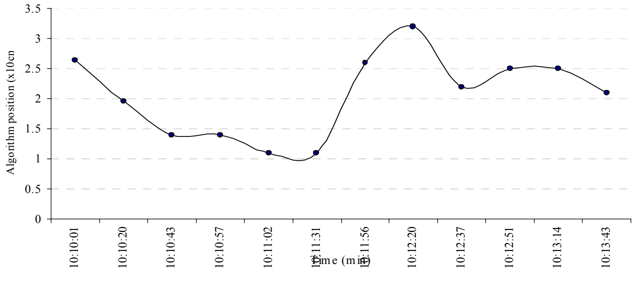

Fig. 10 Capsule Position (Algorithm)

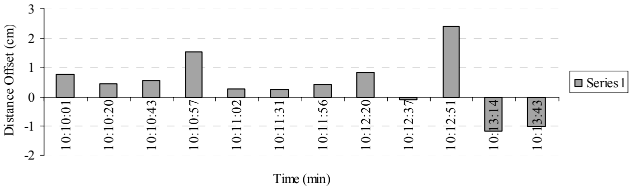

Fig. 11 Location Error

in Fig. 11

V. CONCLUSION

An average error of about 25% was recorded for most of the position measurements, and this is quite acceptable for the capsule tracking application. It was observed in section I (A) that the accuracy of distance measurement using this method is influenced by a couple of antenna, receiver and transmitter related factors. Also, we have observed that there exists a direct relationship between how often the moving object position was sampled. Consequently, When the frequency of sample measurement increased to 5 minutes from the pre-set 10 min, the error dropped to 21%. This can be seen in the logic of segment length computation based on Fig. 8 in which we can conclude that the accuracy of length L can be increased by shortening the segment. The simulated radiation pattern of the dipole is also adequate for the required coverage necessary for tracking application.

ACKNOWLEDGEMENT

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