A Multi-cell UWB-IR Localization System for Robot Navigation

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Abstract - **UWB-IR is an excellent choice for high precision indoor localization. However due to its short range, a multi-cell based implementation is necessary to cover large indoor area. Such multi-cell systems require the use of robust techniques to overcome issues that adversely affect the localization accuracy at inter-cell boundaries. In this paper, the techniques used and experimental results obtained for a multi-cell UWB-IR robot navigation system are discussed. A robust methodology based on boundary detection and path prediction is proposed. Using the proposed methodology, an RMS localization estimation error of less than 15cm is achieved at all positions within the localization space including the inter-cell boundaries.**

Index Terms — **UWB, Localization, Multi-Cell, Robot Navigation, TDOA.**

I. INTRODUCTION

The high precision localization accuracy provided by UWB-IR (Ultra-Wideband Impulse Radio) makes it an ideal solution for several applications such as Robot navigation, personnel tracking and tracking of high value assets in indoor environments. However, due to relatively low transmit power levels allowed by the various regulatory bodies, the range between tracked mobile nodes and stationary reference nodes is limited. Hence to cover a large localization space, it has to be segmented into smaller cells, leading to a multi-cell based system.

In a multi-cell localization system, each cell will be monitored by a set of reference nodes. As it is not possible to isolate the radio coverage of each cell, there will be significant overlap of coverage between cells. In such situations, there will be several possible solutions for the position of the mobile node. But only some of the solutions would be accurate estimates of the mobile node's position. Furthermore, there is also a higher chance of RF front-end saturation near the cell boundaries due to closer proximity between the mobile and reference nodes. Thus, there are specific issues to be handled in a multi-cell localization system as compared to single cell localization system.

While several works [1-3] have been reported in the literature on single cell localization system, there appears to be a dearth of papers dealing with the issues of a multi-cell implementation. Hence, this paper discusses the system, methodology and results for an experimental multi-cell test-bed. The test-bed was setup to study UWB localization for Robot navigation and tracking application.

II. SYSTEM CONFIGURATION

Locating a node in a wireless system involves the collection of location information from radio signals traveling between the target node and a number of reference nodes. Various positioning techniques: Angle-of-Arrival (AOA), Received-Signal-Strength-Indication (RSSI), Time-of-Arrival (TOA) and Time-Difference-of-Arrival (TDOA) can be used to determine the location of the node.

Since UWB-IR makes use of very narrow pulses, it is possible to easily distinguish between the first arriving direct pulse (assumed to be line-of-sight) and reflected pulses. So, the utmost advantage of UWB-IR for localization is achieved by using time based techniques. Consequently, TDOA was the chosen technique for the system described in this paper.

A typical implementation of TDOA methodology would involve the use of 4 static Reference Nodes or Readers whose positions are known apriori. The mobile node would be a transmitter and the pulses generated by the mobile node are received by the 4 Readers. The 4 Readers would then downconvert the received UWB RF pulses to baseband pulses and send them to a central processing and control unit (CPCU). At the CPCU, based on the time difference of arrival of the pulses at the receivers, the position of the mobile unit is computed and displayed graphically. In the multi-cell system, each cell is monitored by at least 4 Readers and the Readers at the boundaries between cells can be shared by all adjoining cells.

The localization space used to test the multi-cell system is shown in Fig. 1. It is segmented into 3 rectangular cells, namely, Cell 1, Cell 2 and Cell 3. The system makes use of a total of 8 Readers, R1 to R8. The Readers are mounted on the false-ceiling and make use of Discone antennas (Fig. 2 and Fig.3).

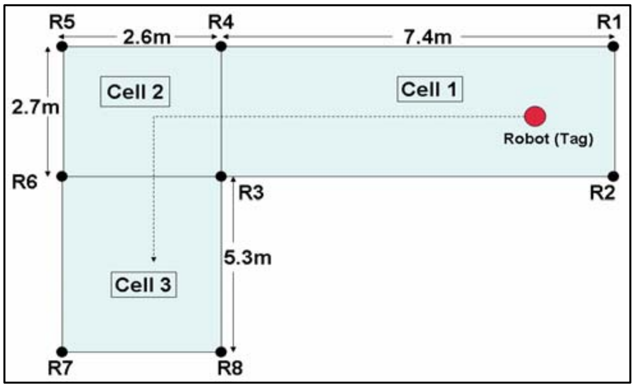

Fig. 1: Geometry of the Corridor (Multi-cell Test-bed)

The Mobile Tag or Node is mounted on a Robot, as shown in Fig. 4. The position of the Robot has to be calculated, tracked and plotted. The UWB pulse transmitted by the tag is shown in Fig. 5(a). The spectral characteristics of the transmitted pulses are shown in Fig. 5(b). The pulse's spectrum (shown in green) has been designed to conform to the FCC spectral mask (shown in red) for UWB transmission [4].

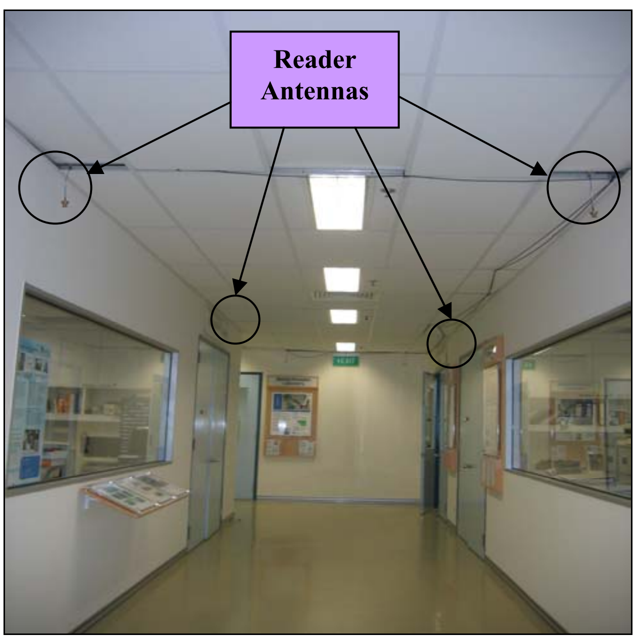

Fig. 2: Layout of the Cell 1 of Corridor

Fig. 3: Zoomed view of Reader Antenna mounted with the Reader on the False-Ceiling

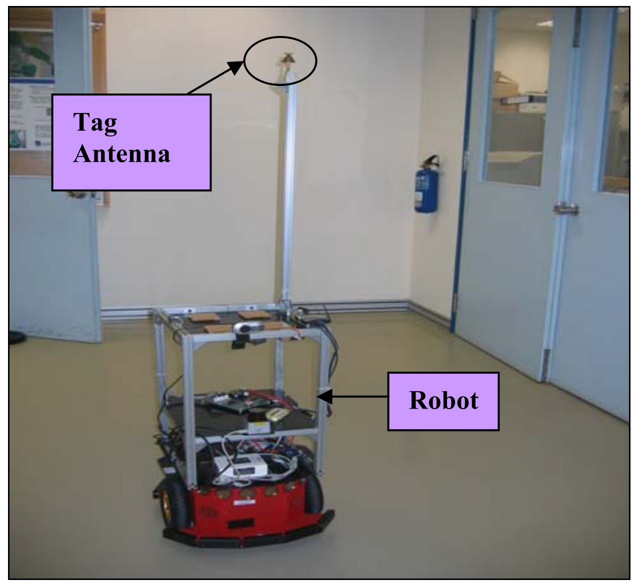

Fig. 4: The Tag being mounted on the Robot

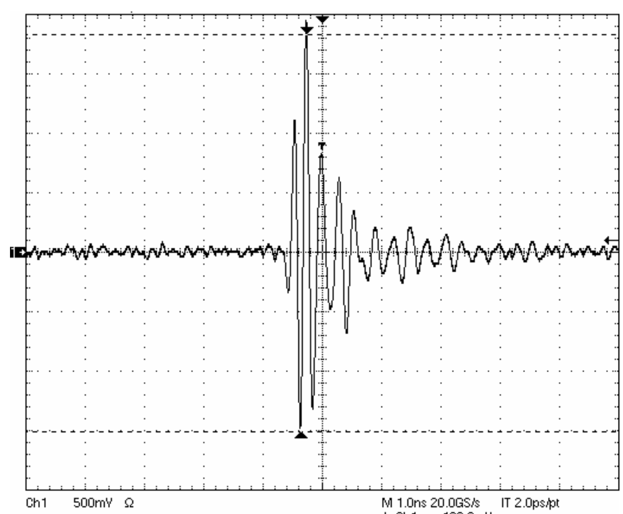

Fig. 5(a): Tag output in Time Domain

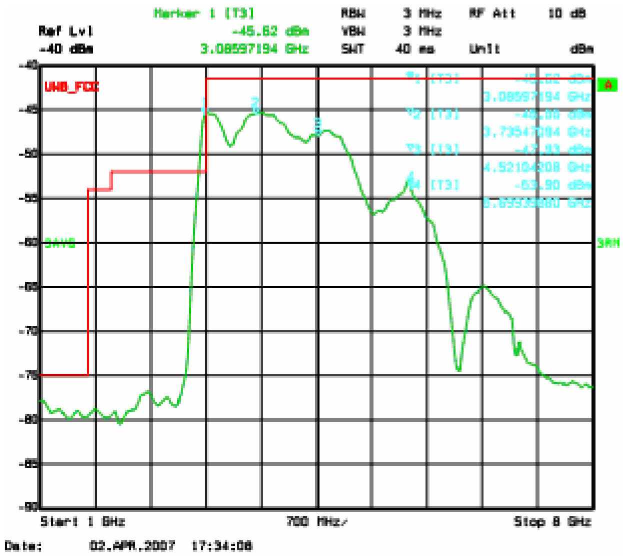

Fig. 5(b): Spectrum of Tag output

III. METHODOLOGY

The main difference between a single cell and multi-cell localization system is the need to handle the issues that arise near inter-cell boundaries. These issues if not handled properly would lead to errors that are larger than those in the rest of the localization space. Particularly, in the proximity of inter-cell boundaries, there are two main issues that contribute to an increase in the position estimation errors:- a) Saturation of receiver RF front-end b) overlap in cell coverage areas.

A. Saturation of receiver RF front-end

It has been shown in [5] that the pulse energy to noise ratio (E_p/N_0) critically affects the timing jitter of the received signals and in turn, the accuracy of a ranging or localization system. In [6] it was shown that the received pulse energy E_p is significantly affected by the combined effect of the gain patterns of the transmit and receive antennas and the range between them. The other component of E_p/N_0, the noise (N_0) is dependent on the bandwidth, gain and Noise Figure of the front-end amplifiers. To keep the noise power low, the receiver's gain has to be as high as possible. While the receiver gain can be adjusted using open or closed-loop variable gain controls, it should be noted that the first stage low noise amplifier (LNA) is most often of fixed gain. It is only the later RF or IF stages that may have variable gain capabilities. Consequently, there is a high chance of the front-end amplifiers getting saturated for short ranges between the transmitting mobile tag and a Reader. This would most likely be the case at positions close to the boundaries, as the tag would inevitably be near to one or more Readers. The saturation of the front-end amplifiers in turn results in a distortion in the shape of the received pulses. As the time of arrival of the pulses at the various Readers is determined by level triggering, a change in the shape of the received pulses would lead to errors in the Time-Difference-of-Arrival calculations [6]. While this is an issue for both single cell and multi-cell systems, it is more serious for the latter as it magnifies the effects of the overlapped cell coverage problem discussed next.

B. Overlap of Cell Coverage Areas

Very often, when the Robot is in a cell, the transmission from the mobile tag would be received by Readers in the boundaries of other cells as well. For example, when the Robot is at the end of Cell 1, as shown in Fig. 1, the signals are only received by Readers R1, R2, R3 and R4. But as the Robot moves towards Cell 2, other Readers, R5 and R6 would also start receiving the signals. When the Robot is at the boundary between Cell 1 and Cell 2, all the Readers (including R7 and R8) will receive the transmissions. Using TDOA, several solutions for the position of the tag can be obtained through triangulation using the data of both sets of Readers. But it is observed that the error in the estimation arrived from Readers of a particular cell, is always larger if the mobile tag is near the triangulation boundary or outside the cell [2,3]. And when the error is large, the estimated position could actually be a point within the cell boundary when the actual position is outside. This means that choosing the correct estimate is not as trivial as choosing the estimate that appears to be within the boundaries of a cell monitored by a particular set of Readers.

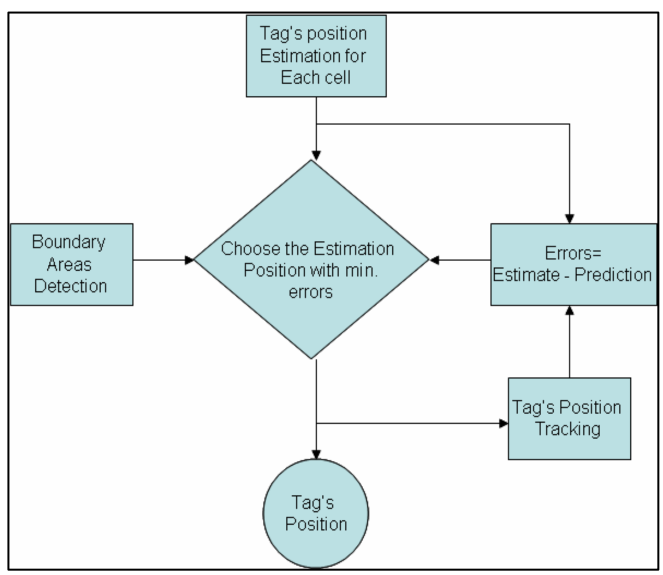

Fig. 6: The Flow Diagram for the algorithm of the Decision of Position of Tag on the Boundary of two Cells

A more robust technique based on the tag's previous estimated position, predicted current position and proximity to inter-cell boundaries is needed to resolve the ambiguities in cell position that arise due to the above discussed two problems. Fig. 6 shows the flow chart for the proposed methodology to choose the correct position estimate near inter-cell boundaries.

The Tag's position is estimated for all cells receiving signals on at least 3 Readers. A prediction is also made from the Tag's past positions. The errors are calculated as the difference of the estimate and the prediction. The final decision for the location of the Tag is taken when the system gets the Boundary area detection condition and calculated value of the errors from the adjoining cells.

IV. RESULTS

The proposed technique for choosing the correct position estimation at inter-cell borders was tested experimentally. For the localization test space shown in Figure 1, the robot was made to move along a certain path from Cell 1 to Cell 3. The results of the robot position estimations are shown in Fig. 7. The tiny 'robots' indicate the estimated position while the solid line indicates the actual position.

Firstly, it can be seen that the TDOA technique has less than 15cm RMS error and 25cm maximum error at any point within the localization space. Secondly, no increase in error magnitude is observed in the transition from one cell to another. This indicates that the proposed method for choosing the correct estimates near inter-cell boundaries is working well, providing almost seamless handover from one cell to another.

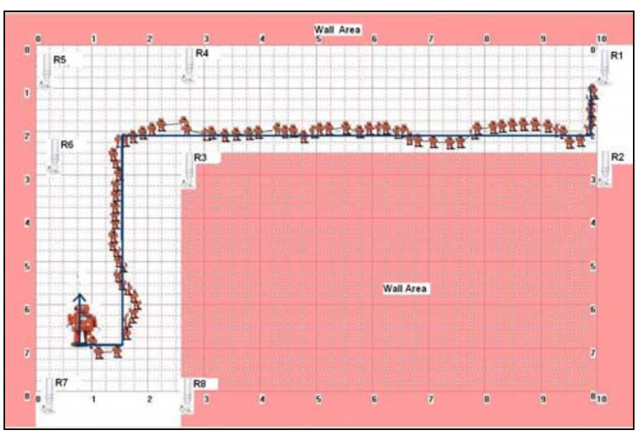

Fig. 7: The snap shot of the Robot tracking on Multi-Cell UWB-IR system.

V. CONCLUSION

It was found that the issues of overlapping cell coverage and saturation of RF front-end were of major concern at inter-cell boundaries in a multi-cell localization system. A robust technique for choosing the best position estimate near inter-cell boundaries is proposed. From experimental results it is shown that the technique is able to overcome the issues at cell boundaries and choose the best estimate, and hence maintaining the high accuracy of less than 15cm RMS error at all points within the localization space.

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