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Radio Tomographic Imaging using Extremely Resource Constrained Devices

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Abstract— **This paper presents a simple and cost effective method for radio tomographic imaging (RTI) using extremely resource constrained devices. The idea is to measure and analyse packet loss rates under various power levels and obtain images of objects in an interested area. We have implemented an experimental prototype for the RTI system using extremely resource constrained devices and results show that the packet loss ratio for RTI is a cost-effective method for image estimation and provides better results when the transmitted power is low.**

***Keywords*— Radio Tomographic Imaging, Line of Sight, Received Signal Strength**

I. Introduction

For most of the recent history, various technological means capable of tracking positions and movements of objects has only been a thing of the military. Sonar, Global Positioning System (GPS), Radio Detection and Ranging Systems (RADAR) are few such technologies which were developed by military funded laboratories entirely for the tactical merit they might provide. Such technologies later found their way into general population and have now grown into a multibillion dollar industry with applications ranging from mundane applications such as Radio Frequency Identification (RFID) tags used in tracking merchandise in a supermarket to Magnetic Resonance Imaging (MRI) used in medical applications. Tomography is also one of the emerging technologies in this area which is used to localize passive objects (Objects which does not carry any tracking devices) inside an area of interest. The word tomography is derived from the Greek word tomos which means sections or sectioning and the process of tomography involves the generation of narrow sections through an object and when it is used with Radio frequencies (RF) it is called as Radio Tomography (RT).Tomography at radio frequencies across large, cluttered environments experiences two major additional complications compared to typical computed tomography (CT) systems.

- Medical tomographic systems have motorized sensors which can be used to measure phase differences at different positions but an RTI system measures only the magnitude of the signal [16].
- Since RF signals have much low frequencies when compared with EM waves it introduces significant non-line-of sight (NLOS) propagations in the transmission and do not travel in just the line-of-sight (LOS) path, instead propagate in many directions from a transmitter to a receiver.

When RTI is done using packet loss ratios it introduces additional problems where environmental conditions (temperature, fog, rain) [2] have a huge impact and it can increase the loss ratios even without obstacles in the LOS path. Despite all those problems when using RF signals, there are many advantages where RF signals such as it can go through obstructions, for example, walls, trees, and smoke, while optical or infrared imaging systems can't. RF imaging will likewise work oblivious, where video cameras will fall flat. Even though RTI systems cannot identify a person it can provide images of the location of people and their locations which on the other hand will improve privacy of individuals something which cannot be achieved by video cameras.

II. Applications

- Smart homes and buildings: Indoor location of a person and identifying the number of people present inside a building could be very useful for various kinds of applications. Especially the accurate localization of people in indoor and domestic environments can be used to automate lights, appliances and air conditioning systems according to the number of people inside a room to reduce the electricity consumption, to observe the tendencies of people etc. [1]
- Reduce Injury in rescue missions: Many law enforcement people are injured each year because they lack the ability to detect and track offenders through building walls [16].With technologies such as RTI, law enforcement and emergency respondents can quickly identify the places they have to focus on and act accordingly to rescue people easily. These devices can be easily used in situations such as earthquakes, building fires etc. to easily identify people who are trapped inside a building without risking the life of emergency respondents unnecessarily.
- Security and monitoring systems: For security and monitoring purposes various devices such as cameras, Infrared sensors or trip-wire based systems have been deployed in the past. Trip-wire based systems can detect when a person cross a boundary but do not track people when they are within the area. When deploying cameras there might be privacy concerns and they might not work in smoky conditions. But RTI based systems don’t have many privacy issues and these devices could be deployed around an area to track people behind a wall or inside a smoky area. [15] RTI based systems act as a trip-wire based system and at the same time it can track people and their location at any

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time inside a building, regardless of availability of lighting or obstructions.

III. Related Work

Radio waves are electromagnetic waves with a frequency ranging from 3 kHz to 300GHz and these waves are affected by the signal frequency, transmission medium and objects encountered. This will result in reflection (the wave partially bounces off an object) refraction (change of direction when passing from one medium to another), absorption (loss of energy when an object is hit), diffraction (when waves are bend and spread around an obstacle), scattering (wave bounces off in multiple directions) and polarization (orientation of the oscillations of the waves can change upon interaction) of the signal.[3] Because of that, signals tend to travel in multiple paths from transmitter to receiver. At the receiver, a phaser sum of waves impinging on the antenna determine the received signal strength.

This phaser sum may be constructive (waves have same phase) or destructive (waves have opposite phase), resulting in a RSS that is a function of the centre frequency and position in space, an effect called multipath fading. When the phaser sum is destructive, the link is in deep fade, and when constructive, the link is in an anti-fade [8]. Researchers have used various equipment's such as software-defined radios, Zigbee's and WiFi to capture multipath constructive and destructive fading effects in an RTI system [3], [5]. While commercially available devices such as Time Domain's Radar Vision [7], Cambridge Consultants' Prism 200 [7] and Camero Tech's Xaver800 [6] uses the ultra-wideband (UWB) based mechanisms. These commercially available devices uses a phased array of radars which transmit UWB pulses and then record the return echoes and estimate a range and bearing. [12]These devices are accurate close to the device, but inherently suffer from accuracy and noise issues at long range due to monostatic radar losses and large bandwidths, and involve only one device which diminishes its accuracy.

Because of its downfalls some relevant research is being called "ultra-narrowband" (UNB) radar [6], [10], [9] systems have been used for through-the wall imaging devices. These systems propose using narrowband transmitters and receivers deployed around an area to image the environment within that area. Measurements are phase-synchronous at the multiple sensors around the area. Such techniques have been applied to detect and locate objects buried under ground using what are effectively a synthetic aperture array of ground-penetrating radars [10]. Because in this paper we use low complexity, non-coherent sensors, we can deploy many sensors and image in real time, enabling the study of tracking moving objects.

Outdoor RTI is very much concern with links characteristics where Patwari et.al have conducted various researches on this direction. Fade levels concept is introduced [11] and the fade level of a link can be calculated using,

$$F_{l,c} = \bar{r}_{l,c} - P(d_l) \quad (1)$$

Where

$$P(d_l) = P_0^n - 10\eta_n log_{10} \frac{d_1}{d_0} \quad (2)$$

Where $\bar{r}_{l,c}$ is the average RSS of link L on channel C measured with no person in the proximity of the link line, and $P(d_l)$ is the theoretical RSS, predicted by using the log distance path loss model [12], for two nodes at distance(d_l) The second equation represents a node-specific log-distance path loss model whose parameters η, P_0, d_0 (i.e., the path loss exponent, reference path loss, and reference distance, respectively), are derived by fitting the average RSS of those links having node n as transmitter. In other works, e.g., [10], a global path loss exponent was estimated by fitting the average RSS of all the links of the network. In this work, by generating for each RF sensor an individual distance-RSS model, hardware variability factors (such as e.g. antenna impedance matching or relative antenna orientation between transmitter and receiver [13]) and local environmental differences (such as e.g. the proximity to the node of dense foliage) are taken into consideration [14].

The fade level can be interpreted as a measure of whether a link channel pair is experiencing destructive or constructive multipath interference (or not): in the first case, the fade level is negative and the link-channel pair is said to be in deep fade; in the latter case, the fade level is positive and the link-channel pair is said to be in anti-fade. However, even in multipath rich indoor environments, the measured RSS does not vary significantly unless, e.g., a human body affects the propagation of one (or more) of the multipath components.

On the contrary, outdoor environmental factors, such as wind, rainfall or snow, introduce a significant variation in RSS even when no person is found in the deployment area.

Patwari and his team measures the effect of the environmental noise on a link channel pair as the variance of the RSS measurements collected when no person is in the proximity of the link line [4]. Thelen and his team [17] found out that radio waves propagate better when there's high humidity (at night and during rain) and other works [18] [19] suggest that fog and rain may have a huge impact on the transmission range of WASN nodes. Boano et al. [20] experimental results show that temperature has a major effect on signal strength and link quality and communications at lower temperature require up to 16% less power to maintain a reliable communication. This is due to the effect of temperature on the hardware and he shows that light rainfall has a negligible impact on signal strength while heavy rainfall can disrupt connectivity.

Distance estimation using packet loss ratios have been conducted by yan et el. [15] Where they have used the power management module on the MCU of a Zigbee device and configured it to transmit a sequence of packets of different sizes in various power levels at the network layer. After performing statistical analysis on the packet loss rates they have been able to approximate the distance between the two zigbee devices. First the transmitter sends a sequence of data packets to the receiver with an embedded Packet ID which increments in each transmission. Since the Zigbee implemented by FreeScale can transmit in 16 different power levels they have used that ability to transmit packets to the receiver in various power levels. If total N packets are transmitted and 20 among these N packets, q_i percent of packets are transmitted using transmission power P_i then they have referred to the vector $q = [q_1 q_2 ... q_6]$ as packet distribution. Upon the packet IDs the host device can calculate the packet loss ratio (PLR) and this vital information is then pass back to the transmitter using the maximum transmission power. Then the transmitter estimates the distance based on the PLR. The overall packet loss ratio is then calculated using,

$$PLR = \sum_{i=1}^{16} q_i . PLR_i$$

Their field test results show that the system gives linear results for larger distances especially for distances greater than 90m the results are better than RSSi calculated distances. Even though there have been researches done using packet loss ratios to find the distance of an obstacle to our best knowledge, packet loss rate has not been used to build up tomographic images on an area of interest (AoI). Our experiment shows that the RTI system can measure the location of an obstacle in an AoI. Other benefits are that it does not rely on network infrastructure and is cost-efficient.

IV. Overview

This paper explores the use of RF packet losses on links between many pairs of nodes in a wireless network in order to image the changes in attenuation that occurs within the area of deployment. In general, when an object moves into the area of deployment, we have found out that links which pass through that object will, on average, experience higher packet losses. We explore the inverse perspective, that is, the use of the measurement of additional packet losses on multiple, intersecting links to image the attenuation within the area and infer the location of an attenuating object. Section V presents a linear mathematical model relating to the packet loss ratio and the software architecture we built for reverse imaging. Section VI derives the setup of an actual RTI experiments which we conducted and the parameters used, and the resultant images. Finally section VII summarizes our work and describe future directions for improving the proposed RTI system.

V. Model

A. Software Architecture

Each node in the RTI system is a small hardware platform consisting of an RF transceiver and a microcontroller. Our RTI system consists with two main nodes where the resource full device is called as the Controller node while the extremely resource constrained device is called as the slave node and those are the only two node types that consists in our system.

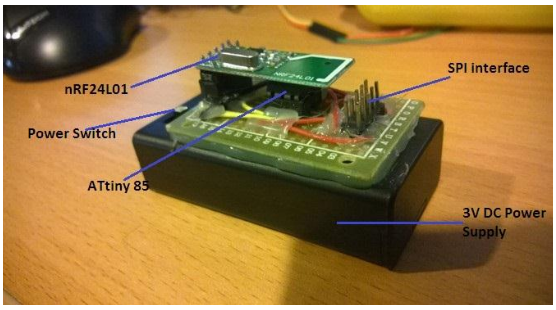

Figure 1: Slave Node

Generally the RTI system contains the following two steps.

Step 1: Controller node sends a request packet to the slave nodes requesting them to send packets in four different power levels to the controller node. The first data packet has ID x, the second data packet has ID x+1, the third data packet has ID x+2, and so on. These data packets are transmitted to slave nodes whose ID's are hardcoded in their microcontroller.

Step 2: When a slave node with ID x receives the request packet from a controller node it will send a 5 bytes long packet to the controller node in four different power levels. Controller node will keep track of the received packets and it will use those packet lost/receive details to build up the tomographic images of the obstacles in the area.

B. Algebraic Formulation

Input Retrieval: Controller nodes are placed in the transmission range of Slave nodes where each controller node can transmit and receive data from each and every slave nodes. If a packet is successfully transmitted from Controller node "A" to Slave node "a" then value of 0 is added to the A.a cell in the Input Data Matrix and a value of 1 is added to the cell if the packet transfer was interrupted.

When the controller node sends a request packet to a slave node and if the corresponding response packet is not received in the predefined interval then the link which corresponds to that is considered to be broken and it will be updated as "1" in the input data matrix.

Input Data Matrix $A = \begin{matrix} A.a & A.b & \cdots \\ B.a & B.b & \cdots \\ \vdots & \ddots & \cdots \end{matrix}$

Image Reconstruction: Line L is given by the general equation.

$$L \equiv Pz + Qy + R = 0$$

Then the normal distance from a point P≡ [a,b] is given by,

$$dist(P, L) = \frac{|\mathrm{Pa + Qb + R}|}{||\mathrm{n}||}$$

Where ||n|| is the norm vector, ||n||=$\sqrt{P^2 + Q^2}$ then,

$$Pa + Qb + R \leq D.\left||n|\right| = D_0$$

For L to be intersected by an object with radius D

$$dist(p, L) = \frac{|\mathrm{Pa + Qb + R}|}{\left||\mathrm{n}|\right|} \leq D$$

Let coordinates of controller node and slave node be X_c, Y_c and X_s, Y_s respectively and centroid of corresponding voxels be (i-0.5,j-0.5) then,

$$(Y_s - Y_c)(i - 0.5) - (X_s - X_c)(j - 0.5) + Y_c(X_s - X_c) - X_c(Y_s - Y_c) = \propto$$

Assuming L represents a general link that is blocked by an obstacle, D_0 can be an arbitrary constant for a given system setup. Then using the mathematical relationship described above we can create a similar relationship for $\propto \subseteq D_0$ such that the value for cell (i,j) is defined as:

$$f(i,j) = \begin{cases} 1\ if, & \propto \leq D_0 \\ 0\ if\ , & \propto > D_0 \end{cases}$$

When dimensions of reconstruction matrix is M × N

$$B = \begin{pmatrix} F_{A,a} & F_{A,b} & \cdots \\ F_{B,a} & F_{B,b} & \vdots \\ \cdots & \cdots & \cdots \end{pmatrix}$$

Where $F_{c,s}$ is given by,

$$F_{c,s} = \begin{pmatrix} f_{1,1} & f_{1,2} & \cdots \\ f_{2,1} & f_{2,2} & \vdots \\ \cdots & \cdots & \cdots \end{pmatrix}$$

Therefore B is a 3D binary matrix with each cell representing a 2D matrix where a value of 1 indicating the possible solutions to path blocked by that corresponding link.

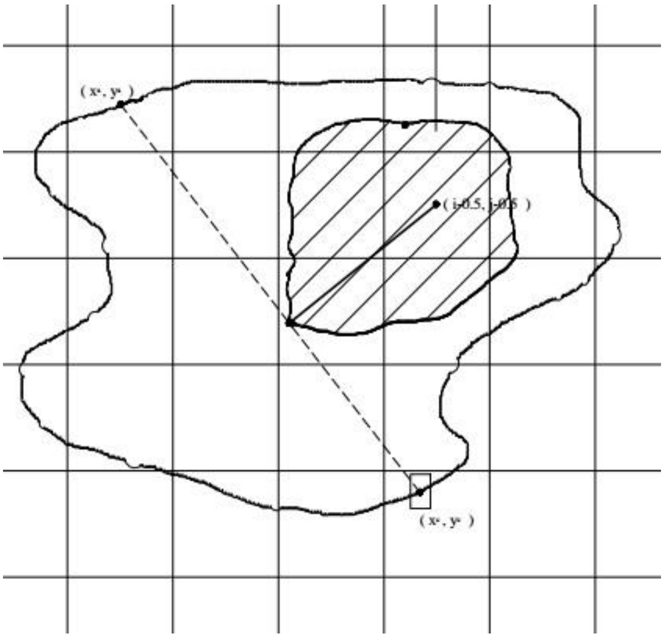

Figure 2: An illustration of a single link in an RTI network that travels in a direct LOS path.

The signal is absorbed by an object as it crosses the area of the network in a particular path and the packet loss ratio starts to increase. Reconstruction matrix was previously defined as M x N matrix in general terms. Thus the resolution of the reconstructed image shall have M x N pixel dimensions. Reconstructed image R with pixel dimensions M x N is given by the Hadamard product of matrices A and B.

$$R = \sum_{y=1}^{j} \circ \sum_{x=1}^{i} (A.B)$$

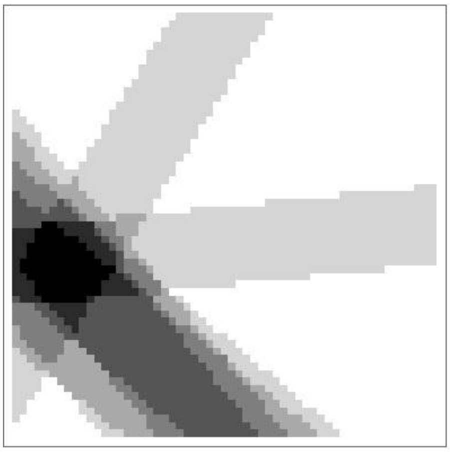

Figure 3: Reconstructed Image with 57x57 pixel dimensions without any refinements

C. Noise Reduction

Noise reduction was primarily achieved by eliminating entries with values under an arbitrary cutoff limit.

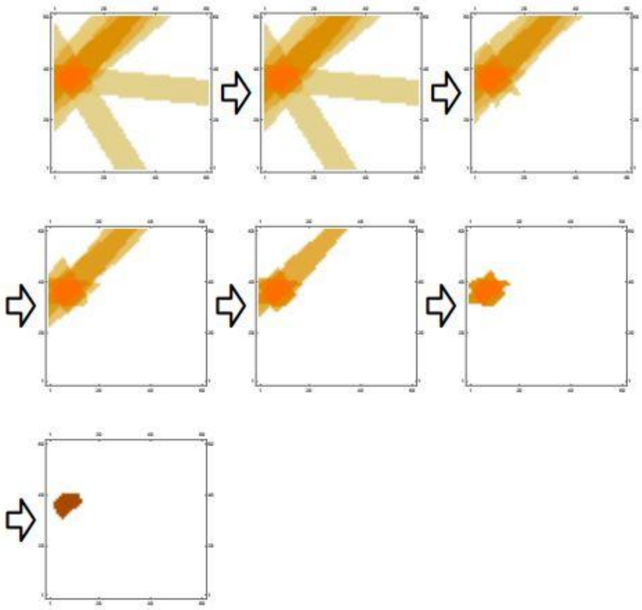

Figure 4: Eliminating entries with an arbitrary cutoff value and refining the image

In each step the value of the high pass filter is increased to narrow down the obstacles location.

D. Further Noise Reduction

Because of noise and other environmental factors packet losses were occurred and some controllers were unable to send packets to the slave nodes at the corner. Because of that an image was taken before any obstacles and then with an obstacle. After that those two images were subtracted to get the tomographic image of the actual obstacle.

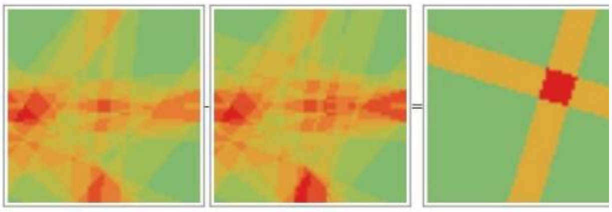

Figure 5: Noise reduction using image subtraction

VI. IMPLEMENTATION AND EVALUATION

A. Slave Node Implementation

Extremely resource constrained device consist with an ATtiny 85 microcontroller operating at 1MHz when active and it consumes 1.8V:300 µA. In power down mode it consumes at 0.1 µA 1.8V. The ATtiny 85 microcontroller is an 8-bit processor with 8Kbytes of flash memory and 512 Bytes of EEPROM memory. Because of this less power consumption of the microcontroller it makes our system much more energy efficient. We have used nRf24L01 as our transceiver in both controller and slave nodes which can transmit data in four different power levels.nRf24L01 is designed for operations in the world wide ISM frequency band at 2.400-2.4835GHz range. It have 250kbps,1Mbps and 2Mbps on air data rates and when used in the lowest power level it consumes only 7mA for the transceiver and this helps in increasing the battery life of the device.

B. Controller Node Implementation

Controller node consists with necessary hardware and software for calculations and it uses the data collected from slave nodes to build up the tomographic image of the environment. We have used an Arduino Uno Rev3 which have an ATmega328P chip as its microcontroller and nRF24L01 transceiver to transmit and receive data from the slave nodes. Arduino Uno Rev3 has 14 digital input/output pins of which 6 can be used as PWM outputs, 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button. ATmega328P consists with 32KB of flash memory and 1KB of EEPROM.

To find out whether it is possible to identify an obstacles location while it is in the line of sight path, we conducted several experiments for that. The very first experiment what we did was to keep the controller node and the slave node 10m apart and put an obstacle in between the LOS (line of sight) path

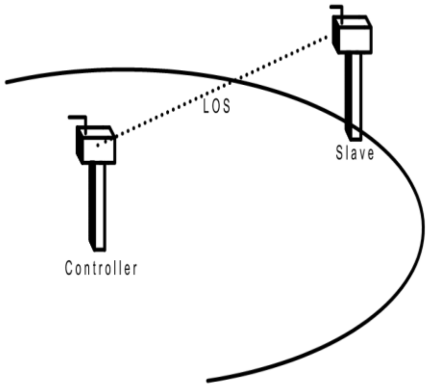

Figure 6: LOS path of Controller node and slave node

We kept the obstacle right in front of the slave node and then got the packet loss count for 3 minutes time. Then we moved the obstacle from slave node to controller node in 0.5m distances and repeat the experiment again. Moving the obstacle in 0.5m was done for 15 times and this whole experiment was conducted 3 times to improve the accuracy of the results. Then we included the results in a one-way analysis of variance (ANOVA) to check whether there are any significant changes in each groups so that we can find an obstacles location by the count of the loss packet ratio.

Received Percentage:

	Sum Of Squares	Df	Mean Square	F	Sig
Between Groups	37.860	13	2.912	.586	.845
Within Groups	139.151	28	4.970		
Total	177.011	41			

ANOVA analysis results yields that the significance level is 0.845(p=.845) which is above 0.05 and therefore we can conclude that there is statistically no significant difference in the mean between groups of transmission power level for different distances. Because of the above experiments it was possible to conclude that it is not possible to measure the location of an object in the LOS path by using the number of loss packets but it is possible to say that if there’s an object within the LOS range there will be a significant drop in the received packets.

With the conclusions taken from the above experiments we made the following test environment to test our tomographic algorithm. An array of extremely resource constrained devices are put in 4 × 4 matrix and this grid was 3m × 3m.Controller Nodes are placed outside as shown in figure 4. so it won’t block or act as an obstacle to the other slave nodes. Then we kept a human obstacle in different places and collect the packet loss details. Finally those collected details were inserted into the reconstruction algorithms and a high pass filter was applied to find the location of the obstacle. Every experiment was conducted around 7:00AM-10:00AM where the ambient temperature was around 25-27 0C and there was less wind and no fog at all. While conducting the following experiments. Controller Node with ID 1 starts and it will send request packets to all the slave nodes in anti-clockwise direction. Then controller Node with ID 2 starts the process and this continue until all four Controllers finish their process and all data are logged in to the RTI reconstruction system.

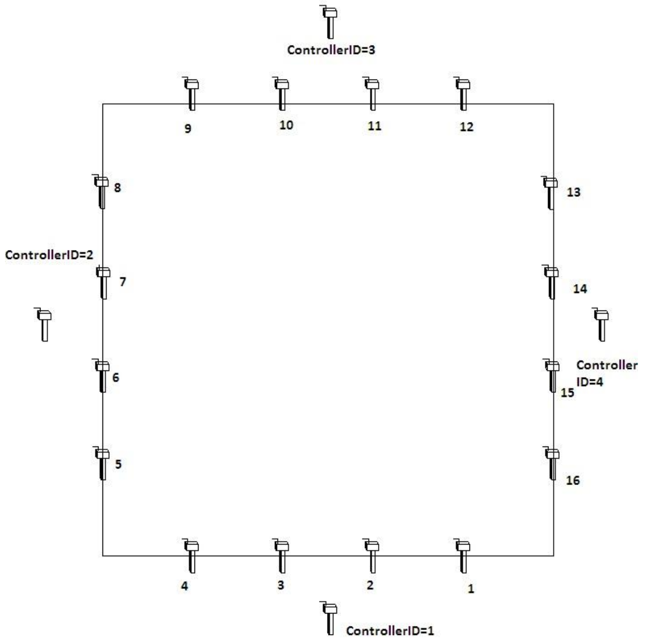

Figure 7: Slave nodes and Controller nodes in an 4x4 array.

Then an obstacle was kept in various locations inside the 3m x 3m area and took the location of it and the location shown by our RTI system was compared to see the accuracy of our system.

With all the experiments conducted it can be clearly seen that the location of the centroid starts to move towards the actual obstacle’s centroid after increasing the high pass filter’s (with the number of refinements are increased) value. At the beginning without any refinements the distance between the actual obstacle and the RTI system’s location differs from 0.8m to 0.2m. Then after 7 refinements the distance between the obstacle and our RTI system starts to decrease and it differs from 0.17m to 0.06m.

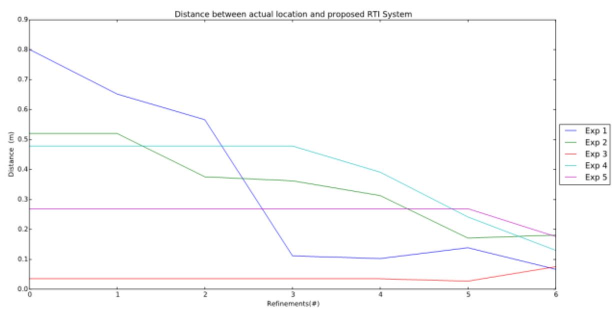

Figure 8: Distance between actual location and the proposed RTI system

VII. CONCLUSION

Radio Tomographic Imaging (RTI) is a method of imaging passive objects within a wireless network. This paper presented a linear model relating packet loss ratio measurements. Theoretic analysis has been carried out and an experimental prototype has been implemented using nRF24L01 transceivers and ATTiny85 microcontrollers. All experimental results are in a good agreement with theoretic derivations. Real measurements have demonstrated that the RTI system is a cost-efficient way of getting tomographic images through a wall providing higher accuracy when used in low power levels.

VIII. CHALLENGES

We encountered two main challenges while building our RTI system.

• Accuracy: Unlike any other Radio Tomographic Imaging system’s which uses RSSI , we are not getting any numerical values as the input but only a binary received/not received indication as the input to our system. Because of that we had to use various methods to improve the accuracy of the system. • Cost Efficiency: One of the objectives of our system is to keep the cost at a minimum level while using extremely resource constrained devices

IX. CONTRIBUTIONS

Radio Tomographic Imaging is an emerging field in which a large number of relatively low-cost radio sensors have been used to detect the presence of objects within an area of interest. In our proposed RTI system controller nodes sends request packets periodically to the slave nodes and use the packet loss ratio to identify the location of an obstacle. Slave nodes which will be listening to the controller nodes request packet will transmit packets in the required power level and this details are used to create the tomographic image by the controller node.

Its strength lies in its simplicity- both in terms of the sensor requirements, and the mathematical algorithms we have used for inverse imaging. We were able to show that RTI with packet loss ratio can be used to estimate the location of an attenuating objects within the area of interest.

In this paper we have proposed a novel approach which is based on a very much popular algorithm called “Algebraic Reconstruction Method (ART)” to do radio tomographic imaging. We have used the packet loss ratio and various power levels to transmit them over air and could potentially be applied in a wide number of situations because the only measurement capability needed in the hardware is the ability to send packets on various power levels, which is a feature included in practically many wireless digital communication devices.

X. FUTURE DIRECTIONS

The proposed approach has opened up new research ideas to focus on many different aspects in RTI field where one can extend this for indoor environments and for bigger areas in outdoor environments. Because of the low transmit capability of the nRF24L01 transceivers which we have utilized as a part of this work, a most extreme scope of roughly 7-25m (in an open region) restricted the extent of the zones where investigations were performed. It would be great if one could extend this research to see if these same conclusions were true for larger areas-areas with a radius with hundreds of meters. Even though we have used some heuristic methods for defining the high pass filter value one can extend this to use a machine learning approach where the accuracy of the RTI system will be much higher and this could be used to identify the movements of a person.

REFERENCES

[1] T. Aaberge. Low complexity antenna diversity for ieee 802.15.4 2.4 ghz phy, Sept. 2009.

[2] F. Adib, Z. Kabelac, D. Katabi, and R. C. Miller. 3d tracking via body radio reflections. In Proceedings of the 11th USENIX Conference on Networked Systems Design and Implementation, NSDI'14, pages 317–329, Berkeley, CA, USA, 2014. USENIX Association.

[3] F. Adib and D. Katabi. See through walls with wifi! SIGCOMM Comput. Commun. Rev., 43(4):75–86, Aug. 2013.

[4] C. Alippi, M. Bocca, G. Boracchi, N. Patwari, and M. Roveri. RTI goes wild: Radio tomographic imaging for outdoor people detection and localization. CoRR, abs/1407.8509, 2014.

[5] G. Anastasi, A. Falchi, A. Passarella, M. Conti, and E. Gregori. Performance measurements of motes sensor networks. In Proceedings of the 7th ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems, MSWiM '04, pages 174–181, New York, NY, USA, 2004. ACM.

[6] K. Bannister, G. Giorgetti, and E. K. S. Gupta. Wireless sensor networking for"hot" applications: Effects of temperature on signal strength, data collection and localization.

[7] C. Boano, N. Tsiftes, T. Voigt, J. Brown, and U. Roedig. The impact of temperature on outdoor industrial sensornet applications. Industrial Informatics, IEEE Transactions on, 6(3):451–459, Aug 2010.

[8] M. Bocca, O. Kaltiokallio, and N. Patwari. Radio tomographic imaging for ambient assisted living, pages 108–130. Springer, Berlin Heidelberg, 2013.

[9] R. Bultitude. Measurement, characterization and modeling of indoor 800/900 mhz radio channels for digital communications. Communications Magazine, IEEE, 25(6):5–12, June 1987.

[10] C. Chang and A. Sahai. Object tracking in a 2d uwb sensor network. In Signals, Systems and Computers, 2004. Conference Record of the Thirty-Eighth Asilomar Conference on, volume 1, pages 1252–1256 Vol.1, Nov 2004.

[11] Y. Chen and A. Terzis. Calibrating rssi measurements for 802.15.4 radios, 2012.

[12] Freescale Semiconductor. MC13192 MC13193 Reference Manual, 7 2006.

[13] A. Goldsmith. Wireless Communications. Cambridge University Press, New York, NY, USA, 2005.

[14] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami. Internet of things (iot): A vision, architectural elements, and future directions. Future Gener. Comput. Syst., 29(7):1645–1660, Sept. 2013.

[15] H. Hashemi. The indoor radio propagation channel. Proceedings of the IEEE, 81(7):943–968, Jul 1993.

[16] J. Wilson and N. Patwari. Radio tomographic imaging with wireless networks. Mobile Computing, IEEE Transactions on, 9(5):621–632, May 2010.

[17] J. Thelen, D. Goense, and K. Langendoen. Radio wave propagation in potato fields. In First workshop on Wireless Network Measurements (co-located with WiOpt 2005), Riva del Garda, Italy, apr 2005.

[18] G. Anastasi, A. Falchi, A. Passarella, M. Conti, and E. Gregori. Performance measurements of motes sensor networks. In Proceedings of the 7th ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems, MSWiM '04, pages 174–181, New York, NY, USA, 2004. ACM.

[19] Dongjin Son, Bhaskar Krishnamachari, and John Heidemann. Experimental study of concurrent transmission in wireless sensor networks. In Proceedings of the 4th International Conference on Embedded Networked Sensor Systems, SenSys '06, pages 237–250, New York, NY, USA, 2006. ACM.

[20] K. W. Kolodziej and J. Hjelm. Local positioning systems: Lbs applications and services. CRC Press, Taylor & Francis Group, 2006.