MODELLING OF SENSOR-BASED NETWORK FOR TRACKING APPLICATION IN MINES

Synopsis of the Thesis to be submitted
in partial fulfilment of the requirements for
award of the Degree of Doctor of Philosophy

by

Arpan Halder

(15MI91R03)

Under the supervision

of

Professor Dr Debashish Chakravarty

Department of Mining Engineering

Indian Institute of Technology, Kharagpur

November 2021

1. Introduction

Worksite situation awareness is an essential part of mining engineering. Due to the safety-critical nature of the mining industry, it is always desired to have state of the art technology and innovation for up keeping the safety with minimal compromise on productivity. For addressing this challenge, the use of Information and Communication-based Technologies (ICT) has the potential to substantially enhance the safety and operational effectiveness of mining industry processes.

For the mining industry real-time position information of working employees and machinery is of high importance due to its potential use in worksite safety enhancement. Position determination and navigation in the surface application can be considered trivial due to GNSS, namely the Global Positioning System (GPS). However, for positioning applications in underground mines, GPS is not available. Therefore for positioning applications in mines, we have to rely on alternative technologies. After the Mine Improvement and New Emergency Response Act of 2006 was passed in the USA, which demanded real-time tracking and two-way communication with all underground operators, research in developing such technologies applicable for underground mines became a trendy topic of research.

2. Motivation

Accident reported from Ananta Opencast of Mahanadi Coalfields Limited: On 03.05.2020 time 05.30 AM, While a workman was travelling on foot through the parking yard of an opencast coal mine, he was run over by a dumper sustaining serious bodily injuries to which he succumbed on the spot.

Accident reported from Churcha Mine of SECL: At 01.10 AM night shift on 30.05.2020, "While the conveyor operator, was trying to remove a coal piece stuck near discharge drum of a running belt conveyor, he was pulled and trapped between the discharge drum and the chute side plate and received multiple injuries to which he succumbed at the spot

Figure 1 Some instances of accidents in Indian mines, where causality could have been avoided if the persons and the equipment involved were being monitored for pre-identification of situations where accidents may occur.

For the mining industry real-time position information of working employees and machinery is of high importance due to its potential use in worksite safety enhancement. If a tracking system is in place for both surface and underground mines, many such accidents like in Figure 1 can be avoided. Whenever a working person enters into a place where he is not supposed to at that point of time, at that moment an IoT enabled system shall be able to raise an alarm before any accident-like situation may arrive. Other than prevention of accidents, having such a human tracking system shall also enable accurate post-accident investigation. Though full-fledged human and machine equipment tracking systems are yet not widely adopted in the Indian subcontinent, research with the motivation of indigenization of such technologies towards identifying the technological gaps and scopes of improvement in this domain shall help in speeding up the adoption of such technologies in the Indian conditions. With this pretext in mind, we felt it is important to work in this domain to investigate the scope of improvement in these technologies such that progress can be made in the direction making these categories of technologies more techno-economically feasible for Indian mining industry applications.

3. Problem

The tracking system for mines has mainly two technical components, 1) positioning system 2) communication network in the backend. In the case of GPS less underground mines, wireless communication networks have a more significant contribution, as radio signals from the wireless access points are one of the primary means for positioning in underground mines in state of the art applications. Because of this reason, the challenge of tracking operation in this work is a combination of positioning and sensor networking challenges in underground mines. Communication infrastructure being one of the primary necessities for communication of position information in tracking; therefore, the optimal placement of wireless access nodes to give coverage to all concerned regions of interest is one of the most important factors.

At this point, several ideas for the improvement of positioning estimate accuracy in mining applications exist. However, there is yet a requirement of analytical study to see up to what extent these approaches will impact the overall system accuracy. Having a more in-depth quantitative understanding of influencing factors, we shall be able to judiciously decide what component of the positioning system needs to be upgraded to get maximum improvement with limited additional investment.

4. Literature Review

Literature covered for this thesis work can broadly be categorized in the following categories:

State of the art practises and research trends in this domain.	(Douglas, 2014) (Puñal, 2016) (Dayekh, 2014) (Griffin et al., 2010; Schafrik, 2013)
Algorithmic approaches for optimal deployment of wireless networks	(Misra et al., 2010; Muduli et al., 2018; Yang et al., 2012) (Singh and Sharma, 2014; Yoon and Kim, 2013)

Data fusion and filtering in IoT aided positioning techniques.	(Gustafsson, 2010; Hu et al., 2008) (Arulampalam et al., 2002; Gustafsson et al., 2002)
Platform tools related to deployment of such systems.	(Morgan et al., 2009) (Cousins, 2011; Cousins et al., 2010; Martinez and Fernández, 2013; Morgan et al., 2009; Quigley et al., 2015).
Safety regulations & statutory requirements.	(Wessels, 2016), DGMS Circulars, Regulations

Few of the notable research works that are in this domain are like the doctoral thesis of (Schafrik, 2013) where (Griffin et al., 2010; Schafrik, 2013) mainly focused on the Underground Wireless Mesh Communication Infrastructure Design, Prediction and Optimization. Next, (Yu, 2015) is another thesis work related to algorithm development for positioning using WiFi signal strength index for underground mine tunnels Then another notable work is (Dayekh, 2014) is a thesis work that discussed the use of machine learning based techniques to model RSSI map of NLOS condition in the mine site. (Puñal, 2016) is another doctoral thesis work that worked towards the development of wireless sensor nodes for rock mass monitoring for the underground mining application.

5. Research Objectives

To address our research problem we have worked upon the following research objectives in this thesis work.

1. To investigate WiFi AP RSSI based positioning techniques and possible sources of errors in such methods for the purpose of developing the sensor model for positioning.
2. To investigate the usability of IMU based methods for human gait analysis to develop a suitable sensor model for position change estimation in mine like situations.
3. To investigate for a suitable multisensory data coupling approach for tracking applications in the mine site, incorporating the mine site layout information in the model.
4. To investigate for a suitable optimization approach for optimal deployment of wireless communication infrastructure considering the objectives and constraints of the mine site.

6. Scope of Work

Following are the scope of the work under each objective of the thesis work

1. For the first objective, a theoretical investigation of the wave propagation patterns in the mine like environment was to be done. First of all, this is important for the development of state observation models (SOMs) that are partly dependent on RSSI. Secondly, this is linked to the fourth objective of wireless infrastructure deployment planning as well, as to ensure the

coverage there has to be an understanding of wave propagation through the mine roadways. For this work, some experiments with real hardware were to be done and then an FDTD based numerical simulation with Maxwell's Equations to further understand the several phenomena observed during the experiments.

2. For the second objective IMU-based gait tracking was studied with experiments to establish the understanding of which part of the body is most suitable for mounting IMUs with the intention of human stride length and direction estimation. And data from several muddy, sandy and undulated roadways were to be collected as well to investigate if there is any notable difference in the IMU signature from those kinds of roadways than flat walking surfaces of their civil applications of such algorithms. So that we may conclude how reliable different stride length and direction algorithms are in such cases.

3. In the third objective, different algorithmic approaches were to be studied to decide a suitable framework for our tracking application in mine sites. Investigative studies were to be conducted to decide for a suitable algorithmic approach for implementation of our HMM based application case. State Observation models for relevant sensors were to be studied for coupling them with the position estimation algorithm. Suitable approaches for coupling SOMs, STMs and map informations were to be investigated likewise, to test the proposed approach with the help of simulation.

4. Under the fourth objective, the objectives and constraints of tunnel-like environments of underground mines had to be mathematically modelled by suitable means, for the development of an optimization framework for optimal placement of wired and wireless infrastructure in underground mines.

7. Work Done

The research problem of tracking can primarily be subdivided into two sub-components, 1) Localization/Positioning technologies 2) Deployment of data communication infrastructure for tracking. The Problem of positioning itself is a vast independent domain with plenty of research questions unanswered. Similar is true for the research domain of communication infrastructure deployment optimization. The most suitable method for data communication infrastructure deployment varies depending on the requirements and the constraints of a particular application case. In this subsection, we briefly go through the methodological approach and the experiments designed to get acceptable answers to our research questions related to the implementations of these technologies in the mining industry application that this thesis work deals with.

To keep the synopsis report brief, all experiments and analysis of the thesis work are not discussed here, only some key results and associated analysis are been discussed to provide an overall outlook.

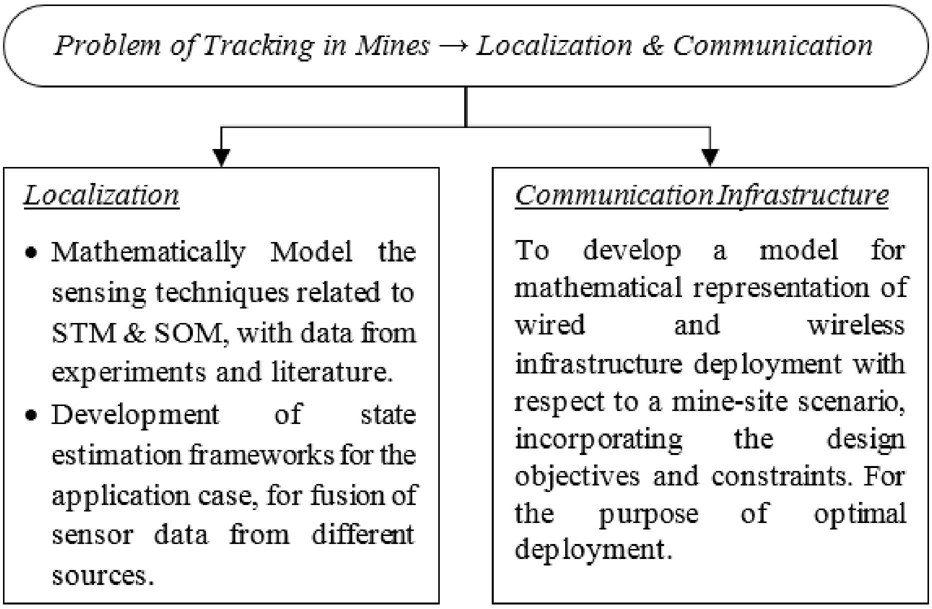

Figure 2 Research components addressed in the thesis

RSSI Based State Observation Model for positioning

For the field study of RSSI maps, we mostly relied on Smartphones and WiFi enabled embedded devices of ES8266, ESP32 series of devices from Espressif Systems and CC3200 based development boards from TI. We initially did several experiments in the tunnel-like environment by recording RSSI values with the help of tracker prototypes, and then visualized the data later after plotting them in the computers However, later for ease of real-time temporal visualization of data, multiple setups as shown in *Figure 3* below was created, instead of first recording the RSSI data and then visualizing it later on a computer like we were doing in the initial stage of this research, this new approach with LED indicator based RSSI visualization for experiments proven to be more convenient. Here we scaled the RSSI values to the HUE scale and lit the connected RGB LED in that particular hue so that we may get and visual interpretation of the RSSI value at a particular place for that particular orientation of the antenna of the module that's measuring the RSSI value.

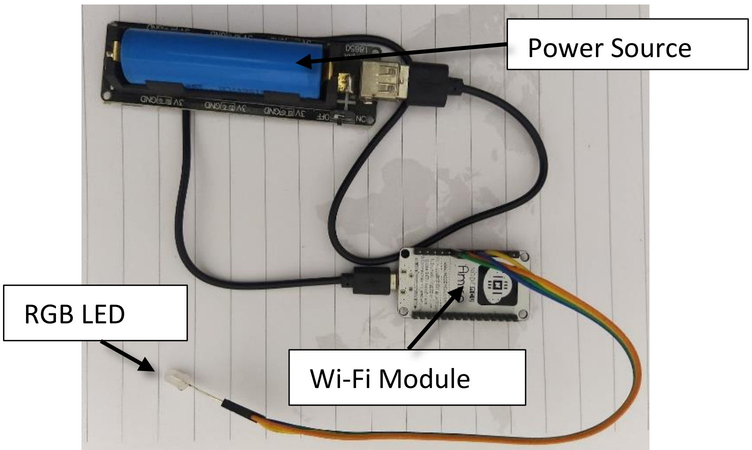

Figure 3 Devised setup of real-time visual observation of RSSI values

With our initial experiments and trials, we had observed that the ESP8266 modules that we were mostly used for the RSSI measurement, loses connectivity when the signal strength drops around -90 dBm and the strength is more than -30 dBm only when the device is in close vicinity of 1-2 m. Therefore, after a few hits and trials, we finally scaled -30 dBm to -80 dBm from HUE scale 340° (Magenta) to HUE scale 0° (Deep Red). Where power level above -30 dBm was equated to 340° otherwise that may reach up to 360° which may visually appear similar to 0° HUE of red. Thereby, we had a visual Scale that is explained in the table below. And for Strength equivalent RSSI value below -80 dBm, the Module is programmed to blink, giving an indication of low RSSI.

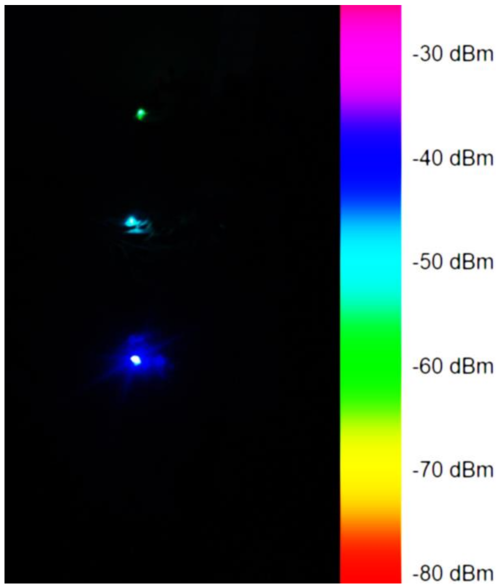

Figure 4 The RGB RSSI receivers placed about 2m apart from each other in an indoor corridor; displaying the values of an AP that is behind the camera. Here we're able to able to

For our experiments, we had observed that the presence of metallic objects hereby significantly affects the RSSI Map of the region. To understand the mechanism behind this distortion we designed an FDTD simulation with Maxwell's equation to develop insights related to its underlying mechanism. For simulation, we took cases like the figures below. Where Figure 5 Represents a small section of a simplified gallery layout of a room and pillar underground mine with pillar width 3m and pillar distance centre to centre distance 13m (Dimensions complying CMR 2017) along with a square metallic block for which the parameters were set in the following configurations: conductivity = 1e7, the dielectric constant was set to a high value as setting it infinity wasn't possible here and relative magnetic permittivity to 2000 that is close to the category of steel that is used to build mining machinery.

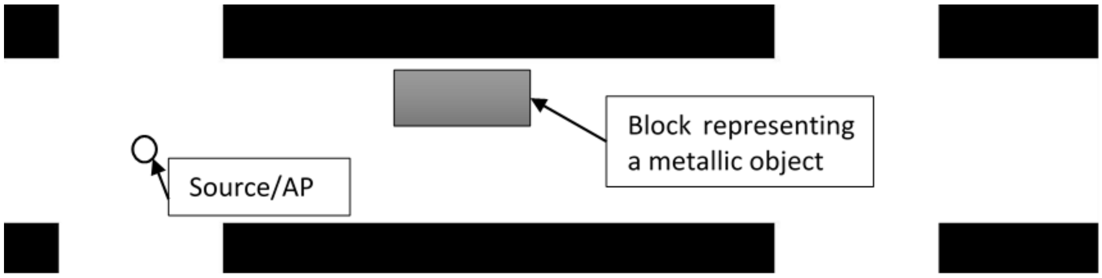

Figure 5 A simplified gallery layout of an underground mine with the Access Point as EM Source placed in the junction with a square block of metal to study the effect of wave propagation pattern in presence of metals.

For the first simulation, we wanted to test our hypothesis that in the presence of metallic objects (i.e. machineries operating in mines) the change in the RSSI pattern is significant. During our physical experiments we measured RSSI values near the metallic doors, and even near metallic collapsible gates and we observed high spatial variance in the measured RSSI values near large metallic objects. Now, this fluctuation is majorly due to exactly which reason, whether it's solely for the presence of a metallic body or something else that we didn't consider? To get a scientific answer to this question we planned for this kind of simulated analysis.

From the figure of the simulated result, we can see that presence of a metallic body affects the RSSI measurement around it, not only by the shadowing effect but also due to strong reflections. Therefore, from this study we could conclude that there is a need for real-time estimation of RSSI map; for accurate estimation of position using such data. Otherwise, the range of variance of the RSSI value shall have to be kept very high in the state observation model (SOM).

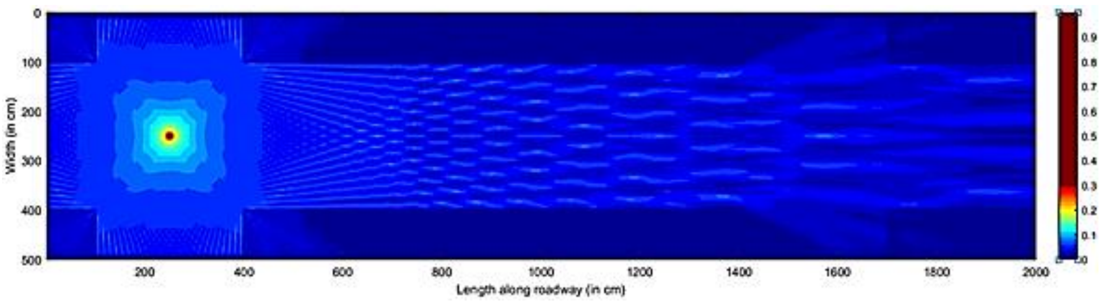

Figure 6 Mean square amplitude of the simulated wave

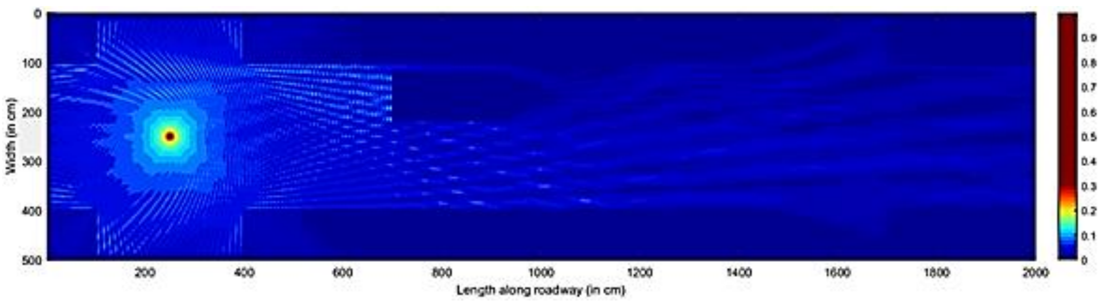

Figure 7 Mean square amplitude of the simulated wave in presence of a sizable metallic object

From the results illustrated in Figure 6 and Figure 7 above we can see the difference in the wave propagation pattern in presence of a sizable metallic object in a tunnel-like environment. Here we can confirm that in the presence of a metallic object the RSSI map all around the object changes due to both reflection and shadowing effects. Therefore in the cases of machineries and tubs, the spatial pattern of the RSSI map in the tunnel-like environment changes. Therefore it'll add to more uncertainty in the RSSI based SOM.

IMU based State Transition Model for tracking application

From this investigative study, the first thing we tried was to infer the pros and cons of the placement of the IMU sensor device in the different parts of the pedestrian's body. After observation of IMU signatures from several individuals, we could observe that the maximum amount of jerk is recorded from the foot-mounted IMU then waist-mounted and head-mounted IMU respectively. The Figure 8 below illustrates this finding in a visual form. That for leg-mounted sensors, instantaneous acceleration reaches almost up to 25 m/s^2 whereas the waist mounter sensor only reaches a level of around 8 m/s^2 and visible spikes on the head-mounted sensor is almost close to 4 m/s^2 level which is very less compared to leg-mounted sensors.

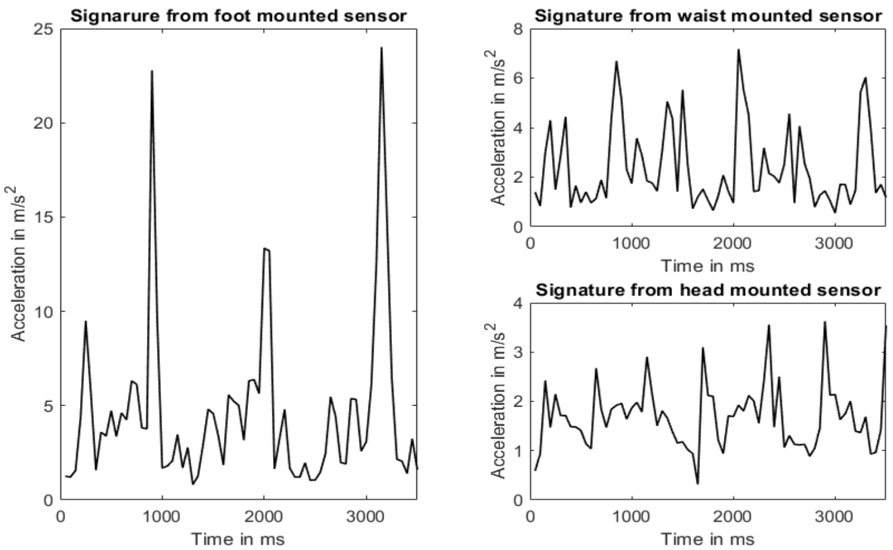

Figure 8 Comparison between heel strike spikes of foot, waist and head mounted accelerometer data.

Other important observations from these early sets of experiments were the fact that even if the sensor is mounted to the right feet, still the jerk from the heel strike of the other feet gets recorded quite significantly. The scale of such detection is even better than the waist-mounted and head mounted sensors. The smaller peaks in the signature captured from the foot-mounted sensors are actually those jerks from the heel strike of the other feet. And there were other experimental observations as well that gave us several other insights related to this estimation process.

Investigation of the performance of Particle Filter for tracking application in UG tunnel like environment.

This study has two components, first simulation of data, and then application of the filter on the simulated data for different filter configuration parameters, following the planned design of the experiment (DOE) that is explained in this section.

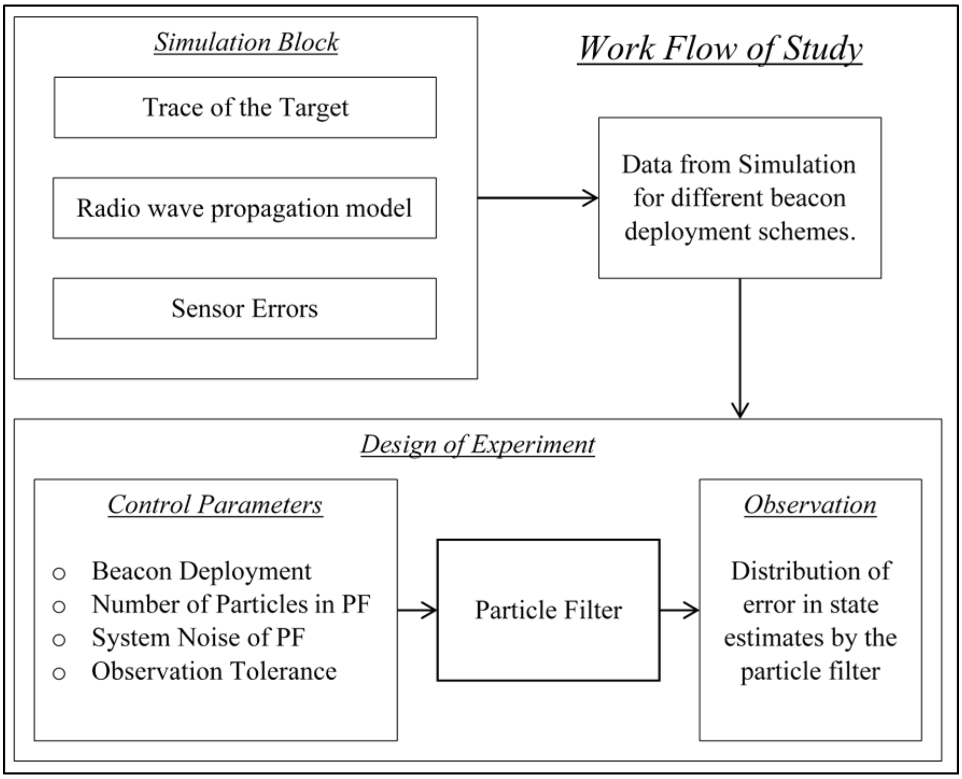

Figure 9 Overview of the Methodology of studying the performance of PF based approach

In our process, we first consider a straight 100m tunnel section with radio beacons placed in the 50m interval. With the three beacons present in our section, one at beginning '*B0'* one at the middle '*B50'* 50m apart from '*B0'* and the last one at another end '*B100'* as shown in Figure 10. Next, in our simulation of wireless positioning operation, we generate simulated RSSI readings along the trace of a moving tracker in this tunnel environment, considering the beacons are emitting radio waves that are propagating through tunnel roadway. How the radio wave propagates through the particular environment, which will decide the RSSI values at different points in the region. The simulation of this process has three main components.

1. The trace of target: In this study trace is a straight line moving at constant velocity.
2. Model errors in RSSI observation by the tracker.
3. Radio Propagation model through the tunnel.

The radio propagation behaviour in the tunnel-like environment has been studied and reported in the literature (Bedford et al., 2017; Patri and Nimaje, 2015; Zhou et al., 2015). Next, there are several distributions for modelling the wave path loss; namely, Rayleigh, Nakagami, Rice, Weibull and log-normal shadowing are among the most commonly used models.

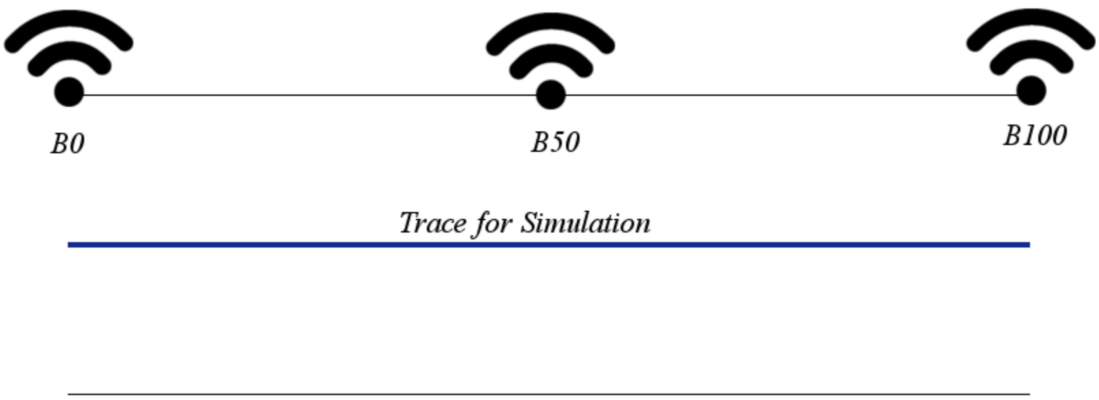

Figure 10 Layout showing beacon positions in the 100m long tunnel section that is considered for simulation.

For our simulation purpose, we choose the Ray-Tracing model considering one reflection for propagation modelling; and for path loss to use the log-distance path loss model. Compared to other models we preferred the Ray-Tracing model for its mathematical simplicity (Forooshani et al., 2013) and ease of implementation for the simulated cases. This study helped us in getting insights into the factors that influence the overall accuracy of the estimation.

Modelling of Network for Optimization

This is investigative work towards identifying a suitable method for wireless infrastructure deployment inside an underground mine. After an initial survey of possible approaches towards solving this problem, we found it appropriate to look into the possibility of the development of a graph theory based framework to mathematically model the objectives and constraints that are relevant to wireless infrastructure deployment planning in underground mines. Where we tried to take advantage of roadway network like features of underground mine layouts to define our region of interests as a set of edges of the network and represented desired objectives and constraints as graph notations. The methodology of the investigative work described in this chapter was to first test the proposed framework on simplified layouts of mine and solve the graph problem with the help of a suitable optimization approach and then after several rounds of fine-tuning, we move to realistic mine layouts and then fine-tune when necessary.

8. Conclusion & Contribution of this thesis

This investigative work tried to further look into the possibilities of effective use of all available information that can aid in position estimation of the men and the machinery in underground mines. Information like the map information, detectable features from IMU readings of the tracker, information from deployed sensors. This utilization was done by developing a sensor fusion model to effectively use this information in the position estimation process. For this purpose in-depth study of wireless radio propagation mechanisms was done via experiments and simulation. After

Furthermore, this work tries to develop a method for the deployment of a communication network in underground mines, fulfilling the required criteria like coverage to the region of interest where tracking is desired, bandwidth requirements, latency etc. Development of a standard method for wireless communication network deployment that accommodates mining industry requirements such as its time-varying nature, coverage of the region of interests and optimally meeting the bandwidth requirements of the particular applications. Following are the key contributions that can be outlined from this thesis work

1. The thesis work investigated the WiFi RSSI map patterns with the help of experimental and simulation approaches. Alongside listing out some of the key physical phenomena that may influence the accuracy of RSSI based positioning systems, their mechanism is also elaborated with the help of analysis done in the thesis work.
2. The thesis work also studied the performance of IMU based methods for the prediction of gait transition of the pedestrians in mine like situations. And pointed out the difference of signature captured from pedestrians in mine like muddy undulated situations to the normal flat surface captured IMU signature. This was important because these differences could lead to errors in the estimation during scaled-up implementation in mine-like situations. And with the help of further study and analysis, the fact is established in the thesis that foot-mounted IMU trackers are the most suitable for gait tracking application where the purpose of such tracking is to establish a state transition model (STM) for moving pedestrians.
3. In the case of tracking in underground mines, the site is mostly a tunnel-like environment. With the simulation approach, the thesis investigated how the placement of radio beacons and other positioning hardware shall effect the tracking. And also studied the effect of different configuration parameters in the proposed PF base filter algorithm in position state estimation in a tunnel-like environment.
4. The analysis of this thesis work also led to the design of Stationary Sensor Units which are designed for scaled-up implementation of tracking in the underground mine layouts. The abstract mathematical approach of looking at this tracking problem in this thesis helped us to logically identify the scopes of improvement; such as effective use of map information and optimal locations of the deployment of stationary sensors' whose data is to be used in the SOMs.
5. The thesis also proposed a graph theory based method to model the network deployment optimization problem in the mine site. And discussed the practical implications and shortcomings of the proposed methods with case studies.

Publications from the thesis work

Halder, A., & Chakravarty, D. (2018). Investigation of wireless tracking performance in the tunnel-like environment with particle filter. *Mathematical Modelling of Engineering Problems*, *5*(2), 93–101. https://doi.org/10.18280/mmep.050206

Halder, A., & Chakravarty, D. (2018). Wireless relay placement optimization in underground room and pillar mines. *Mathematical Modelling of Engineering Problems*, *5*(2), 67–75. https://doi.org/10.18280/mmep.050203

Conferences

Halder, A., & Chakravarty, D. (2016). Designe Approach for Implementation of Low Cost Indigenous Telemonitoring Setup for Mining Industry Applications. West Bengal State Science Congress 2016, Kolkata Organized by DST Govt. of West Bengal.

Halder, A., Chakravarty, D., & Dey, U. K. (2020). Design considerations of a IoT aided data acquisition system for mining industry applications. In *Advances in Mining (AIM-2020)* (pp. 202–212). Advances in Mining (AIM-2020) Organized by CSIR-CIMFRAt: CSIR-CIMFR, Dhanbad.

A patent application under process

Halder, A., Chakravarty, D., & Dey, U. K., A SYSTEM AND A METHOD FOR DETERMINING LOCATION OF A SUBJECT IN AN UNDERGROUND MINE, being jointly filed by BIT Sindri & IIT Kharagpur

9. References

Arulampalam, M.S., Maskell, S., Gordon, N., Clapp, T., 2002. A tutorial on particle filters for online nonlinear/non-Gaussian Bayesian tracking. IEEE Trans. Signal Process. 50, 174–188.

Bedford, M.D., Kennedy, G.A., Foster, P.J., 2017. Radio transmission characteristics in tunnel environments. Trans. Institutions Min. Metall. Sect. A Min. Technol. 126, 77–87.

Cousins, S., 2011. Exponential growth of ROS. IEEE Robot. Autom. Mag. 18, 19–20.

Cousins, S., Gerkey, B., Conley, K., Garage, W., 2010. Sharing software with ROS. IEEE Robot. Autom. Mag. 17, 12–14.

Dayekh, S., 2014. Smart Localization in Underground Mines using Fingerprinting and ANNs : Strategies and Applications. Québec.

Douglas, A., 2014. Status of Communication and Tracking Technologies in Underground Coal Mines. Theses Diss. Eng.

Forooshani, A.E., Bashir, S., Michelson, D.G., Noghanian, S., 2013. A survey of wireless communications and propagation modeling in underground mines. IEEE Commun. Surv. Tutorials 15, 1524–1545.

Griffin, K.R., Schafrik, S.J., Karmis, M.E., 2010. Designing and modeling wireless mesh communications in underground coal mines. SME Annu. Meet. Exhib. 2010 296–299.

Gustafsson, F., 2010. Particle filter theory and practice with positioning applications. IEEE Aerosp. Electron. Syst. Mag. 25, 53–81.

Gustafsson, F., Gunnarsson, F., Bergman, N., Forssell, U., Jansson, J., Karlsson, R., Nordlund, P.J., 2002. Particle filters for positioning, navigation, and tracking. IEEE Trans. Signal Process. 50, 425–437.

Hu, X.L., Schön, T.B., Ljung, L., 2008. A basic convergence result for particle filtering. IEEE Trans. Signal Process. 56, 1337–1348.

Martinez, A., Fernández, E., 2013. Learning ROS for Robotics Programming: A practical, instructive, and comprehensive guide to introduce yourself to ROS, the top-notch, leading robotics framework, Book, Community experience distilled. Packt Publ, Birmingham.

Misra, S., Hong, S.D., Xue, G., Tang, J., 2010. Constrained relay node placement in wireless sensor networks: Formulation and approximations. IEEE/ACM Trans. Netw. 18, 434–447.

Morgan, Q., Brian, G., Ken, C., Josh, F., Tully, F., Jeremy, L., Eric, B., Rob, W., Andrew, N., 2009. ROS: an open-source Robot Operating System. In: ICRA Workshop on Open Source Software. Kobe, p. 5.

Muduli, L., Mishra, D.P., Jana, P.K., 2018. Application of wireless sensor network for environmental monitoring in underground coal mines: A systematic review. J. Netw. Comput. Appl. 106, 48–67.

Patri, A., Nimaje, D.S., 2015. Radio frequency propagation model and fading of wireless signal at 2.4 GHz in an underground coal mine. J. South. African Inst. Min. Metall. 115, 629–636.

Puñal, P., 2016. Efficient IoT Framework for Industrial Applications. Dr. thesis.

Quigley, M., Gerkey, B., Smart, W.D., 2015. Programming Robots with ROS A Practical Introduction to the Robot Operating System, Journal of Chemical Information and Modeling. " O'Reilly Media, Inc."

Schafrik, S.J., 2013. Evaluation and Simulation of Wireless Communication and Tracking in Underground Mining Applications. Virginia Polytechnic Institute and State University.

Singh, A., Sharma, T.P., 2014. A survey on area coverage in wireless sensor networks. In: 2014 International Conference on Control, Instrumentation, Communication and Computational Technologies, ICCICCT 2014. pp. 829–836.

Wessels, C.H., 2016. To IOT or not IOT : a critical analysis of the key legal considerations applicable in internet of things of implementations in the mining industry.

Yang, D., Misra, S., Fang, X., Xue, G., Zhang, J., 2012. Two-tiered constrained relay node placement in wireless sensor networks: Computational complexity and efficient approximations. IEEE Trans. Mob. Comput. 11, 1399–1411.

Yoon, Y., Kim, Y.H., 2013. An efficient genetic algorithm for maximum coverage deployment in wireless sensor networks. IEEE Trans. Cybern. 43, 1473–1483.

Yu, J., 2015. A Layered Two-Step Hidden Markov Model Positioning Method for Underground Mine Environment Based on Wi-Fi Signals. Mid Sweden University.

Zhou, C., Plass, T., Jacksha, R., Waynert, J.A., 2015. RF Propagation in Mines and Tunnels: Extensive measurements for vertically, horizontally, and cross-polarized signals in mines and tunnels. IEEE Antennas Propag. Mag. 57, 88–102.