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Zinonos, Zinon

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Radio Propagation in Industrial Wireless Sensor Network Environments: From Testbed to Simulation Evaluation

Zinon Zinonos
Computer Science Department
University of Cyprus
1 University Avenue 2109
Aglantzia, CYPRUS
zinonos@cs.ucy.ac.cy

Vasos Vassiliou
Computer Science Department
University of Cyprus
1 University Avenue 2109
Aglantzia, CYPRUS
vasosv@cs.ucy.ac.cy

Tasos Christofides
Department of Mathematics and Statistics
University of Cyprus
1 University Avenue 2109
Aglantzia, CYPRUS
tasos@ucy.ac.cy

ABSTRACT

In recent years, sensor networks characteristics have led to incremental utilization in different types of applications. Several techniques have been proposed to evaluate the performance of WSNs; the two most popular being mathematical analysis and simulations. An important drawback of these techniques is that they provide evaluation results that usually are not similar to those of real deployments. One reason for this is the fact that both techniques introduce physical layer modeling assumptions, which do not usually corresponded to real-life environments. In this paper, we used measurements from an industrial environment to develop a new radio propagation model for use in simulators and mathematical tools. The proposed radio model was implemented in the COOJA simulator and validated against real-life results obtained from a testbed inside a running oil refinery, which were found not to conform to any legacy radio propagation model. The proposed model has been shown to successfully match the refinery testbed behavior.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless Communication, Distributed Networks; I.6.5 [**Simulation and Modeling**]: Model Development

General Terms

Design, Experimentation, Measurement

Keywords

Radio Propagation, Mobility Management, Industrial testbed, Simulation, Performance Evaluation

1. INTRODUCTION

The growth of wireless sensor networks utilization has generated research attention in systems that need to provide certain performance assurances. Nowadays, there is also an increased interest from industrial operations to use sensor networks, due to the low deployment and maintenance cost that they can provide. A number of sensor network applications are envisioned to be applied to industry settings. Examples of these applications could be production monitoring and actuation, safety and worker health-care monitoring, and material and equipment tracking. Despite the fact that there are several research proposals for wireless sensor network usage in industrial environments not many of them are deployed in reality. This is due to the fact that real deployments in industry allowing the evaluation of the applications are difficult to achieve, or they are not continuously available. Therefore, the majority of the researchers evaluate their solutions using simulation tools. The main limitation faced in such evaluations is the mismatch between model and real-life settings. It is common to have an algorithm/system/protocol that works perfectly in a simulation environment, but when deployed in a real setting it just fails. One of the main reasons for this failure is the fact that simulations do not utilize representative radio propagation models but they just rely on theoretical radio propagation models.

In this paper, we used measurements obtained from a prolonged measurement campaign in an oil refinery to propose a new radio propagation model for use in simulations. This was part of the work implemented in the context of an FP7 European project, named GINSENG [1]. One of the project partners is the Petrogal Oil Refinery at Sines, Portugal, which is the largest refinery in the Iberian peninsula and stands among the largest in Europe. The refinery is a multifaceted industrial facility that includes a wide range of processing units that need careful monitoring and control of operations. The refinery environment is unpredictable with high levels of electromagnetic interference and with metal structures and pipes acting as obstacles to radio communication. This is something that makes any similar modeling endeavor extremely difficult, but also highly important. The proposed radio model was validated by matching the performance of the simulated network to that of the real network, both in conditions involving static nodes and those in which mobile nodes were also present.

The paper is organized as follows: Section II presents related work; Section III introduces the application scenario and Section IV presents the proposed radio propagation model. In Section V experimental evaluation and perfor-

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mance analysis are presented and, finally, Section VI concludes the paper.

2. RELATED WORK

Several radio propagation models have been proposed in the literature and are used in mathematical and other analyses. The main way to categorize those models is on the distance separating the transmitter and the receiver. The two main categories are the large-scale propagation models, which predict the average received signal strength over large distances (hundreds of meters or kilometers) and the small-scale propagation models where the distance between transmitter and receiver is of some meters. The small-scale propagation models target to characterize the fluctuations of the received signal in greater granularity. Figure 1 shows our view of taxonomy for the propagation models.

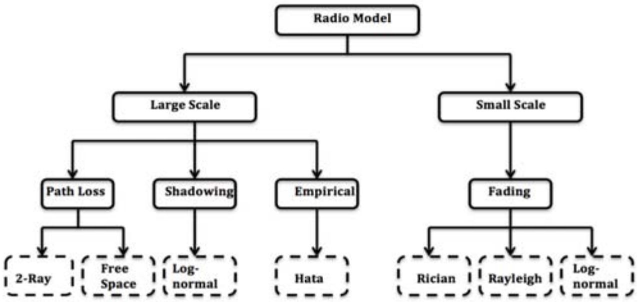

Figure 1: Radio Model Taxonomy

In addition, propagation models can be classified into theoretical and empirical. Both theoretical and empirical-based models indicate that signal decreases logarithmically with distance. The most known theoretical propagation model is the free-space propagation model and is used to predict the received signal strength when the sender and receiver have clear line-of-sight. In the free space model the received signal strength falls off proportionally to the square of distance. The assumption of a non-obstacle environment makes the free-space model not realistic. A theoretical model named 2-Ray Ground Reflection is also used, which considers both a direct path and a ground reflected path between sender and receiver. The 2-Ray Ground model provides accurate prediction over distances of several kilometers.

On the other hand a more complex model is the log-normal shadowing radio propagation [5] where the received signal strength does not depend only on the distance between transmitter and receiver, but also includes a zero-mean Gaussian distributed random variable that accounts for the attenuation caused by buildings or any obstacles between a sender and a receiver. An advantage of the log-normal shadowing radio propagation model over the two aforementioned models is the fact that it does not consider a perfect environment without obstacles.

The most well known empirical model is Hata's model [2] which is an empirical formulation of the Okumura model [3] and is considered to provide the best accuracy in path loss prediction for cellular and mobile system environments. The Hata model is considered to work best in urban and sub-urban areas but the main drawback of this model is that it cannot respond to changes in terrain, therefore it is not suitable for rural areas.

In the case of small-scale models, fading is the most observed phenomenon. Fading is the deviation of the attenuation affecting a signal over certain propagation media and it can happen due to shadowing, called slow-fading or due to interference among signals propagating over many paths to the receiver, called fast-fading. An example of a model capturing the slow-fading is the log-normal model, while Rician and Rayleigh distributions are often used for fast-fading models.

3. APPLICATION SCENARIO

3.1 Application description

One of the applications that were considered in the context of the GINSENG project was the real time monitoring of mobile workers while they are performing regular maintenance in hazardous areas of the refinery. The motivation behind this scenario is the fact that while working in such typically toxic atmosphere there is a possibility for a worker to loose consciousness or become dizzy and fall. For example, based on Figure 2, we have three possible receiver nodes (indicated by the numbers 1, 2 and 3). The mobile worker at the beginning of his trip is attached to the receiver node 1. When the mobile worker is near to receiver node 2, the communication link with receiver node 1 is still good therefore there is not any need to handoff. But as the mobile node is far away for receiver node 1, it has to handoff to a new position. Possible new connection points are receiver nodes 2 and 3, but based on the communication quality the mobile worker will prefer to connect with receiver node 3.

Figure 2: Refinery Mobility Scenario

The mobility requirements for Personnel Safety scenario are the following:

- Data Delivery: The data sent by the mobile node must arrive to the sink node within one second.
- Packet loss: Few packets can be lost. The packet loss for mobility scenario must be as close to the targeted packet loss of the scenarios that no mobile nodes exist, which is no more than 1% of the total sent packets.
- Network: The network is consisted of 1 sink node, 12 fixed nodes and 1 mobile node.

- Topology: The nodes construct a 3-2-1 tree topology meaning that at each time there are 2 free available positions for the mobile node to handoff.

- The TDMA MAC epoch duration was set to one second.

- The mobile node data frequency is more or equal to one second.

- The mobile node sends periodic upstream data to the sink. No burst data are created.

- The data can be time-critical or not.

3.2 System Architecture

The aim of the GINSENG project was to develop a performance controlled Wireless Sensor Network that is well suited for situations in which dependable and deterministic WSNs are needed. To achieve this goal it was understood, early in the project, that besides any mechanisms at the OS and MAC levels (TDMA-based medium access protocol called GinMAC [7][8]) that ensure stable and accurate timing of crucial task scheduling and packet delivery, another set of controlling mechanisms had to be developed. The main assumption of the constructed network is that the target topology is a tree-based topology as shown in Figure 3. The additional functionalities and services that allow the network to meet application specific performance targets are grouped under the heading of Topology Control. Topology control is an important approach in Wireless Sensor Networks (WSNs) to reduce energy consumption, while maintaining network connectivity and capacity. The result is an increase in network lifetime, which is important for wireless sensors that run on battery. Another aspect of Topology control is to coordinate nodes in order to reduce interference between nodes. Power savings aside, less interference can provide a more reliable, thus more predictable, network environment. In our system a dynamic tree formation is considered. Among others, the goal of the Dynamic Topology Control (DTC) [11] module is to connect all nodes in the network and organize them in a tree structure topology (Figure 3) to serve the needs of GinMAC. Therefore in case of mobility management, DTC is responsible to provide possible tree positions to support the handoff procedure.

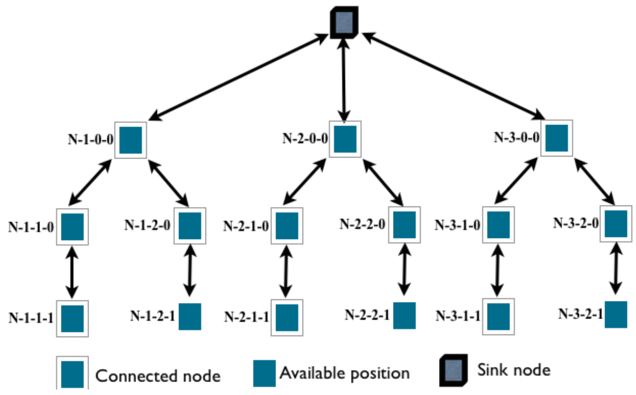

Figure 3: Tree Topology

3.3 Mobility Solutions

Since workers are mobile objects, a mobility management protocol that will efficiently maintain the connectivity of the mobile node by controlling the handoff procedure is required. In order to efficiently monitor or control a mobile person moving inside a testbed area consisted of WSN, the mobile entity must be able to handoff between different networks while performing its movement. Our approach to provide mobility support for mobile workers resides on the fact that we have to control the handoff procedure, which means that at a first stage we have to control the handoff triggering procedure. Due to the limitations of the sensor nodes it was decided that the design of the mobility support would use as much as possible existing information so that to avoid imposing any additional overhead to the system. In addition, our target was to provide a distributed solution, meaning that there is no central entity that has full knowledge of the system and will decide about the handoff procedure. Therefore, all the information that is used is locally available at each node and no communication overhead is added.

The first metric that was used for handoff triggering was the Received Signal Strength Indicator (RSSI). Even though arguments exist about the applicability of RSSI in such environments, there are some works like [**?**] where the importance of RSSI as a suitable metric was argued. In order to support the mobile workers' movement we have implemented and evaluated the S-GinMOB solution [6][9][10]. Based on that work it was shown that although RSSI could help, it could not provide a solution with acceptable performance. Due to the unpredictability of the environment, one cannot rely solely on RSSI, therefore a solution that can combine information using more than one metric is needed. The metric that we used in addition to RSSI is the link loss. Since our environment is not expected to perform linearly but dynamically, we decided to use fuzzy logic to combine the information and to control the triggering procedure. Therefore, we implemented an intelligent controller, based on fuzzy logic, in order to help sensor mobile nodes to decide whether they have to handoff to a new position or not [**?**].

To evaluate our solutions, we used both simulations and real testbed evaluations. For the simulations we used the COOJA simulator [4] (initially with the free space radio propagation model). Table 1 summarizes the packet loss and the number of handover triggers that were obtained from simulation and testbed experiments. The main drawback of the simulations results is that the free space radio propagation model that was used could not match the testbed results.

Table 1: Mobility Results

	Packet Loss (%)	Triggers	Handoff
Simulation RSSI Threshold	1.31	9.18	3.49
Simulation Link Loss	1.74	4.55	1.7
Simulation Fuzzy	0.89	8.08	4.8
Testbed RSSI Threshold	8.11	108.5	4.5
Testbed Fuzzy	2.45	18.5	1.5

4. RADIO PROPAGATION MODEL

It is obvious that the simulations can be used to optimize and compare the behavior of the different mobility solutions but fails to give values that correspond to the testbed evaluation results. This drawback was the motivation for further investigating and modeling the radio propagation model of the refinery environment.

4.1 Radio Measurements

Using the functionalities of a Dynamic Topology Control module, we constructed several network trees to obtain as many different links with different distances and obstacles. Using the 3D Euclidean distance formula, we calculated the distance between all the possible links. Since our testbed consisted of 13 nodes there are 156 possible links but due to the difficult environment (a lot of obstacles and metal constructions) not all the communication links were possible. We managed to obtain 132 unique link observations. Based on our calculations the maximum distance between nodes in our network is 29 meters. Therefore, we can characterize our model as a small-scale propagation model.

Modeling the environment as having a log-normal loss we obtained Equation 1:

$$-10*\beta*log(\frac{d}{d_0})+X_{dB} \tag{1}$$

where X_{dB} is a Gaussian random variable with zero mean and standard deviation σ_{dB}. Based on [5] the value of σ_{dB} was selected to be equal to 6.8.

Figure 4 shows the relationship between the distance, the obtained RSSI values in the refinery environment and the theoretical radio propagation models. In case of the log-normal model we show the ranges of the possible values using the upper and lower possible limits given the X_{dB} value. It is obvious that the obtained values correspond neither to the log-normal model nor to the free space model. As a consequence, we decided to proceed with further investigation of the refinery model.

In addition to the instantaneous obtained values, we observed the variation of the RSSI value for each link. The experiments were run for a long time (11 days) in order to collect enough data. The obtained values were averaged. Except the average values per distance, we measured also the variation of the RSSI per node. Since our network architecture is consisted of static and mobile nodes we wanted to understand how the RSSI is changed for different types of nodes. Therefore, we observed that for the static nodes the sigma value between the obtained signal was 0.65 whereas in case of the mobile node the sigma value was 4.85. It is obvious, as expected, that the mobility of the node affects the received signal strength. We have not yet managed to provide a correlation between specific mobility models and measured signal strength values, since this is part of ongoing investigation. This fact, however, does not reduce our ability to characterize correctly the environment for static and limited-mobility nodes.

4.2 RSSI Statistical Analysis

The data consist of 132 observations whose summary statistics are given as follows:

Table 2: Statistics Summary

Min	1st Q	Median	Mean	3rd Q	Max	St.Dev
-90	-64.25	-57.50	-57.34	-48.75	-27.00	12.27

Exploratory statistical analysis shows that the distribution of the data exhibits reasonable symmetry (indicated also by the fact that the sample mean and sample median are very close to each other). The histogram, boxplot and density of the data indicate that, indeed, the distribution of the parent population is symmetric (Figure 5). In addition, the normal qqplot (quantile-quantile plot), i.e., the plot of the ordered values of the data versus the corresponding quantiles of the standard normal distribution is fairly linear indicating that the data are reasonably Gaussian.

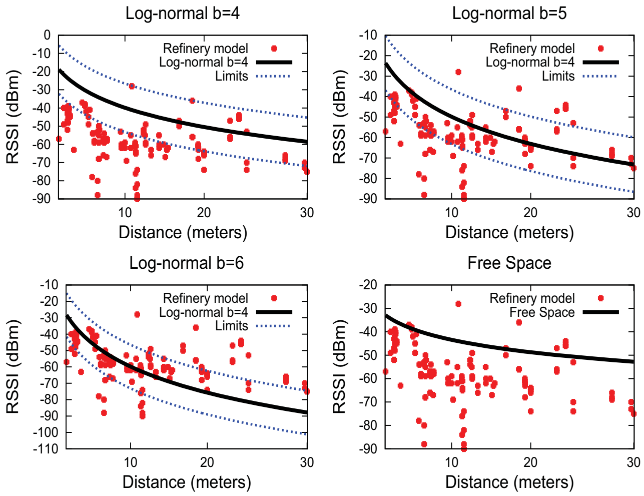

Figure 4: Comparison with theoretical values of free-space and fading models

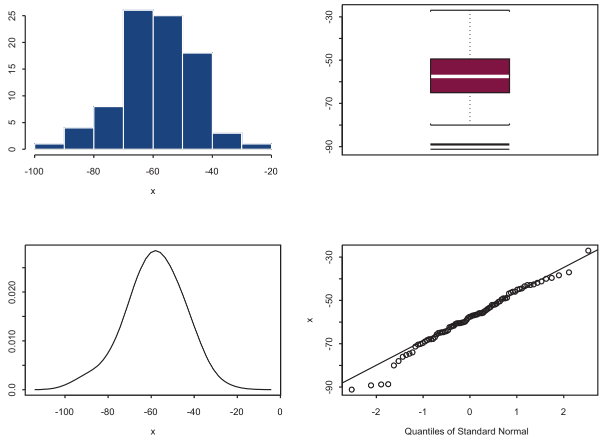

Figure 5: Histogram, boxplot, density and quantile-quantile plot of the data

The assumption of normality is further substantiated by comparing the empirical distribution function of the data with the theoretical normal distribution function. The two distribution functions are very close to each other, as can be seen in Figure 6.

The visual findings of the exploratory statistical analysis can be verified by means of statistical tests. Two statistical tests, the chi-square goodness of fit test and the one sample Kolmogorov-Smirnov test for testing composite normality, both verify that, indeed, the data are normally distributed. The chi-square goodness of fit test for testing the null hy-

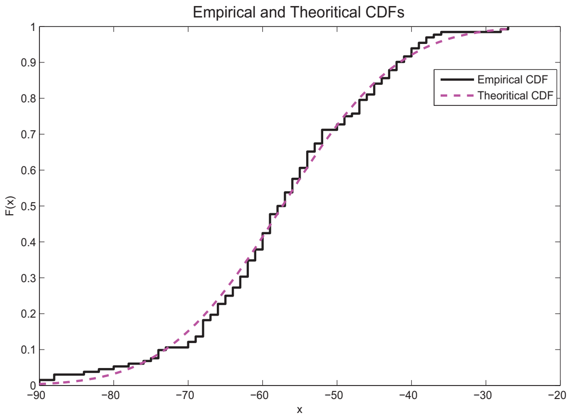

Figure 6: Empirical distribution function of the data and the theoretical normal distribution function

pothesis that the data are normally distributed versus the alternative that the cumulative distribution function does not equal the normal distribution for at least one sample point gives a p-value of 0.42, and thus, the assumption of normality cannot be rejected at any reasonable level of significance. Similarly, the one sample Kolmogorov-Smirnof test for testing the null hypothesis that the data follow the normal distribution versus the alternative that the true cumulative distribution function does not equal the normal distribution produces a p-value of 0.352. As a consequence, the null hypothesis cannot be rejected at any reasonable level of significance. Based on the two statistical tests (which both are considered to be very strict) and the exploratory statistical analysis, it is safe to conclude that the data are normally distributed.

4.3 Link Loss Analysis

In addition to analyzing the RSSI behavior, we proceeded with the evaluation of how the RSSI affects the Packet Reception Rate (PRR). Analyzing the refinery testbed logs we extract the relationship shown in Figure 7.

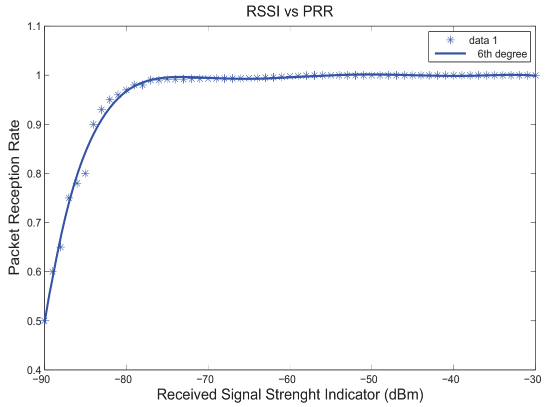

Figure 7: RSSI relationship with Packet Reception Rate

Based on Figure 7 it is clear that we can successfully deliver packets, with negligible packet losses, if the RSSI is above -70dBm. Those losses are slightly increased until -80dBm and beyond that the the losses are increased exponentially and the PRR drops significantly. We use a 6th order polynomial formula to fit the data as it is shown in Equation 2. The obtained formula is the following:

$$y = p1*z^6+p2*z^5+p3*z^4+p4*z^3+p5*z^2+p6*z+p7 \quad (2)$$

where the coefficients are: p1 = -0.011723, p2 = 0.030365, p3 = -0.00043912, p4 = -0.039766, p5 = 0.009391, p6 = 0.015609, p7 = 0.99552 and the norm of residuals is 0.063323. In addition, z is centered and scaled with $z = (x - mu)/sigma$, where $mu = -60.1$ and $sigma = 17.753$.

5. PERFORMANCE EVALUATION

Based on the above conclusions, we implemented the new radio propagation model, as a normal distribution function, and we also used Equation 2 to calculate the link loss. The new model was ported to the COOJA simulator and several sets of tests were performed in order to identify if the new model manages to capture successfully the refinery radio conditions. The first test that we run was to identify if the proposed model statistics (mean and sigma) in COOJA simulations match the real testbed statistics. Table 3 summarizes the simulator obtained values and the testbed values.

Table 3: New model vs testbed results

	Mean	Sigma	Sigma next value
Simulation fixed	-58.46	11.77	0.71
Testbed fixed	-58.17	11.79	0.65
Simulation mobile	-67.84	11.51	4.74
Testbed mobile	-70.39	11.22	4.85

It is obvious that based on the arithmetic values we managed to simulate with high accuracy (minimum match of 97%) the refinery radio model obtained values using the COOJA simulator. Figures 9,8,10,11 show the behavior of RSSI over the time for both fixed and mobile nodes. Those figures show that the proposed radio model managed to simulate correctly and accurately the refinery environment.

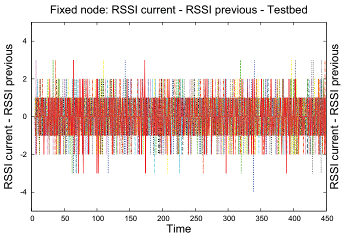

Figure 8: Fixed nodes RSSI values using testbed

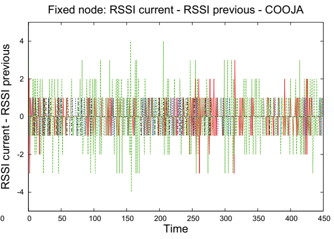

Figure 9: Fixed nodes RSSI values using proposed model in COOJA

In order to evaluate our proposed solution using the mobile worker application scenario, we run a number of tests using the COOJA simulator and the proposed radio propagation model.

Figure 12 shows the reliability comparison of the mobility solutions. Based on the results the obtained packet loss for fuzzy-based mobility solution using our model in COOJA is 2.8% where the actual testbed value was 2.45%, which

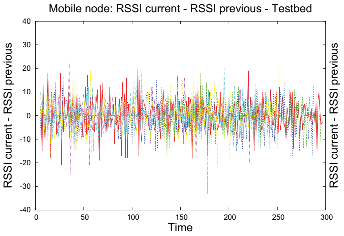

Figure 10: Mobile nodes RSSI values using testbed

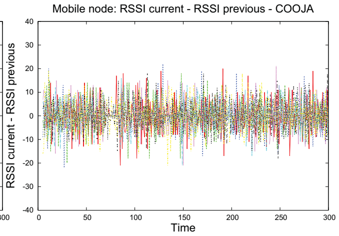

Figure 11: MN RSSI values using proposed model in COOJA

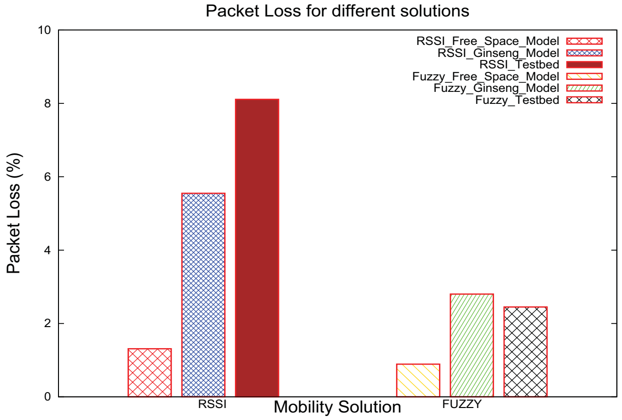

Figure 12: Reliability comparison

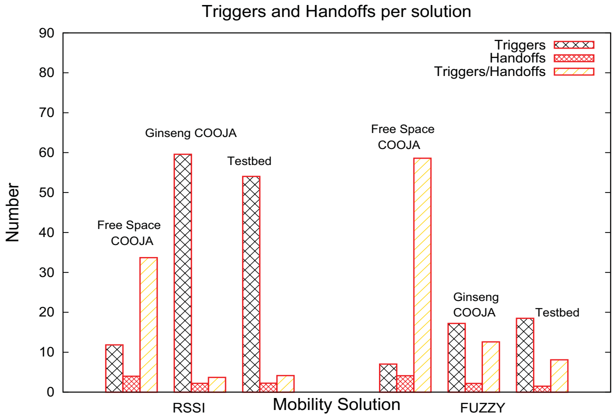

Figure 13: Triggers vs Handoffs

means that the difference of 400% experienced without the model is down to 12

In addition, Figure 13 shows the number of triggers and handoffs per solution. Again it is obvious that the proposed radio model values are closer to the refinery testbed values. For example for the number of triggers in the real testbed we got an average of 18.5 triggers for Fuzzy-based and 54.04 triggers for RSSI-based. Using our model in COOJA we got 17.21 for Fuzzy-based and 59.58 RSSI-based. That means a match of 93% and 90% respectively. If we consider the Free Space model in COOJA then these values are 38% and 21.9% respectively.

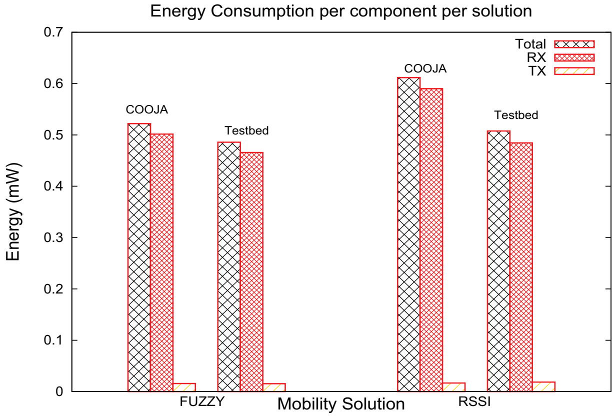

Figure 14: Energy comparison per component per solution

Furthermore, we calculated the energy consumption per component for the proposed model using COOJA and for the testbed experiments. Figure 14 depicts those results. Its obvious again that the results in COOJA are close to those in the refinery. The total average match for the energy components is 90% where the match for the Fuzzy-based is 94.9% and for the RSSI-based is 84.7%.

6. CONCLUSIONS

Moving from simulation environments to real testbed is a high-risk procedure. This is true mostly because the performance evaluation using simulation rarely corresponds to the real testbed performance. Performance evaluation in harsh industrial environments are not common, therefore, the results produced by simulators cannot be justified for their correctness. In this work we tried to address this problem by proposing a new radio model that was implemented, evaluated, and compared using real data from a harsh industrial environment, as is the Petrogal Oil refinery in Portugal. The main target of this work was to be able to simulate the refinery behavior using a simulation tool. Our choice of simulation environment does not preclude the model's successful use in other settings, including mathematical analyses. The selected application of mobile workers allowed us also to observe differences of received signal behavior using fixed and mobile nodes. The results clearly show that indeed the proposed model gives network performance values that are closer to the refinery performance.

Acknowledgements

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